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September 1983

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Under Agreement NCC 3-7

for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
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PREFACE

This book is written for those concerned with making wind turbines a safe and reliable energy source. Although several wind turbine manufacturers have incorporated lightning protection into their designs, the basic principles and design techniques used for lightning protection of wind turbines are not available in a single publication. We hope this book will assist wind energy manufacturers as they examine all the factors of a wind turbine environment.

After alerting the Wind Energy Conversion System (WECS) designer to the hazards of lightning, the techniques for protection are discussed. It is hoped that the text is "user friendly" and the suggested techniques can be incorporated into the wind turbine designs. Even though the fundamentals of lightning protection remain the same, new components and techniques are being developed. If the wind turbine designer develops an understanding of the fundamentals and works with lightning protection component manufacturers, the results should be a protection system which makes the turbine relatively free from lightning damage.

The organization of the text is shown in outline form in the table of contents. Chapter 1 presents an overall view of the lightning protection problem. Chapter 2 covers some important fundamentals concerning lightning, wind turbine structures, and grounding. The remaining chapters cover the special topics of generating equipment protection, electronics protection, and blade protection.

This work would not have been done without the funding provided by the Department of Energy through the National Aeronautics and Space Administration at Lewis Research Center, under the Cooperative Agreement NCC 3-7. We acknowledge their support. H.V. Bankaitis of NASA assisted us by providing information and suggestions as we gathered and put together the information in this book. Several suggestions made by Leonard Gilbert of NASA are incorporated in the text.

Experience with lightning in aerospace and power industries have been a good source of information. Besides looking at past and current literature, several reviewers have made valuable suggestions. Dwight Suiter of NASA made some helpful comments. The suggestions offered by F. Dawalibi were used to strengthen Chapter 2. Keith Crouch of Lightning Technologies, Inc., also reviewed the text. David Begley's contributions on fiber optics and electronic-component damage are appreciated. The suggestions by Don Cunningham have made the text more readable.

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Chapter 1

INTRODUCTION

This book provides information about lightning protection of wind turbines. Because significant amounts of energy can be produced from the wind it is important to have a reliable turbine. Providing lightning protection will make wind systems more reliable and beneficial.

Because areas of favorable location for wind turbines coincide with areas of thunderstorm activity, lightning protection systems need to be provided for wind turbines. The maps of Figure 1.1 [1] and Figure 1.2 [2] show that in most areas where the wind energy density is high there are 30 or more thunderstorm days per year. Both the experimental Mod-0 wind turbine at Plum Brook, Ohio, and the experimental 17-m Darrieus Turbine at Sandia Laboratories in Albuquerque, New Mexico, have received lightning strikes that damaged electronics equipment [3]. The Mod-0 machine also had a kilowatt-hour meter destroyed and puncture damage to the blade.

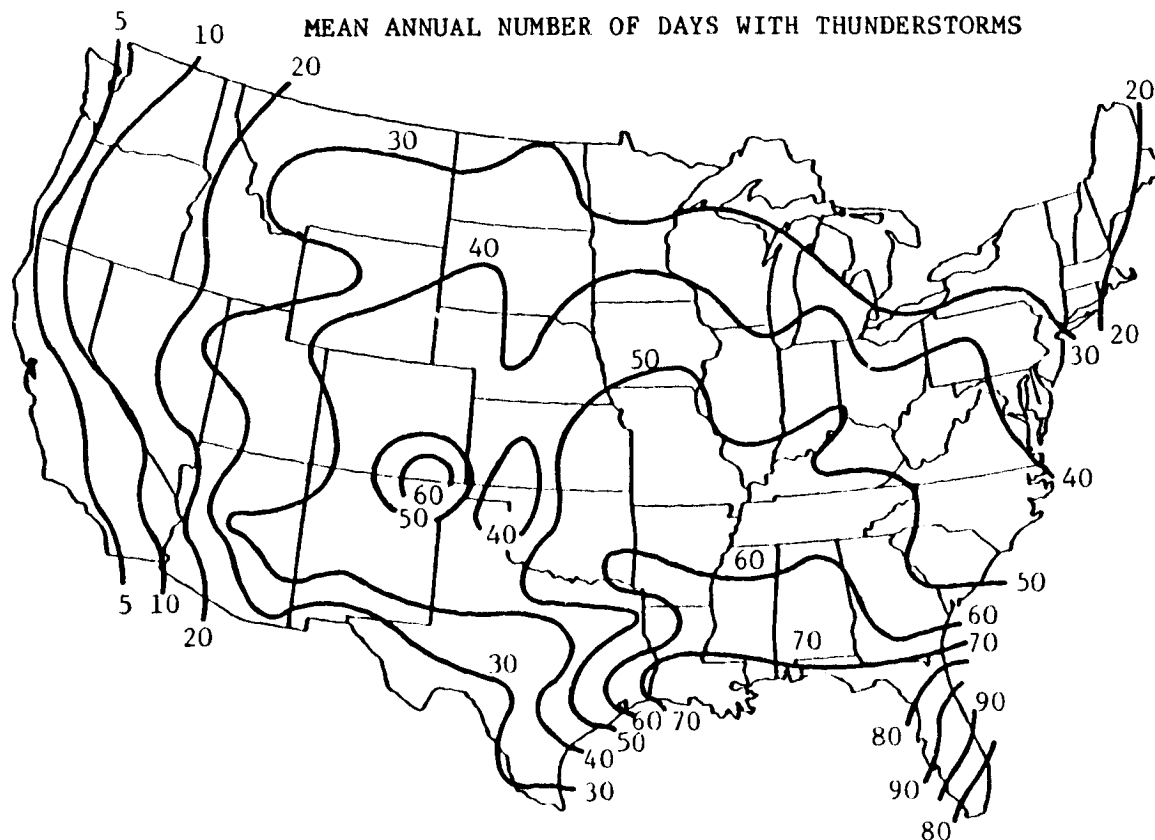


Figure 1.1: Thunderstorm Days Within the Continental United States.

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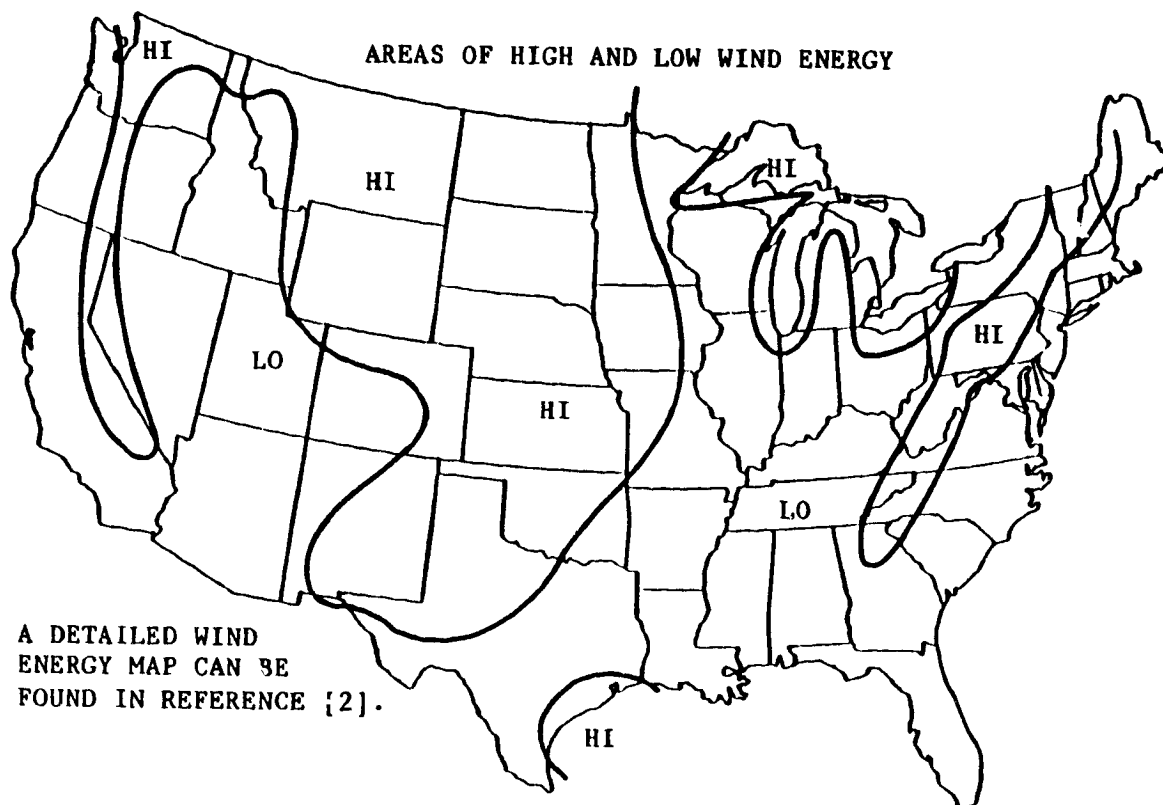


Figure 1.2: Wind Energy Distribution in the Continental United States.

A wind turbine array located in an area that has 30 days of thunderstorms per year and covering a square mile would average around four strikes per year [4]. This means about one strike per 7.5 thunderstorms that pass over the wind turbine area. The damage to this wind turbine array will depend on the characteristics of the wind machine, the power and instrumentation cable connections, and the magnitude of the strike.

It is important to remember that wind turbine components are more exposed to lightning damage than are the components of ground based plants. The electrical and mechanical components mounted on a tall structure placed in an open area are exposed to a more hazardous lightning environment than components mounted at ground level in an enclosed building. Strikes directly to turbine blades, towers, instrumentation, and electrical components will occur.

It should be pointed out that experimental machines will receive more lightning damage than production model machines. Experimental machines normally have more electronic equipment and this equipment is highly susceptible to damage from overvoltage. Because personnel are normally around experimental machines, safety precautions must be taken when thunderstorm activity is in the area.

The amount of damage occurring to the different parts of a wind turbine depends on many factors. Since the peak current in a strike may vary from a few thousand amperes to over 200,000 amperes, the current characteristics of the lightning strike are an important factor.

In the protection of transmission lines, substations, and transformers, utility companies normally expect some damage even though protection is provided [5]. The same philosophy is adopted in the protection of wind turbines from lightning damage. As the quality of protection improves the cost will increase. Wind turbine designers must make cost judgements when considering lightning protection.

The methods of protection explained in this book are based on the theory that lightning damage is minimum if a low-impedance path to ground is provided. The low-impedance path causes much of the lightning current to flow away from components susceptible to lightning damage. The general plan of this book, therefore, is to discuss the following topics:

- o Installation of Good Ground Systems
- o Protection of Generating Equipment
- o Protection of Electronics
- o Protection of Blades

Protection of the blades, the bearings, the generator, and the electronic components all require that a good ground exists at the turbine site. Existing codes discuss methods of obtaining a ground and partially define what is meant by a good ground. Chapter 2 contains design direction for personnel responsible for installation of ground systems at the turbine site. Ground system design should be considered early in site selection and preparation procedures.

Generators on towers are susceptible to lightning from strikes on the tower and from currents induced on the power lines. The standard techniques used by the power industry are applied to line surge protection of generators [6]. However, because currents also may enter from blade strikes or nacelle strikes, standard protection techniques give only partial protection to the generator. The generator control equipment for synchronous machines contains semiconductor electronics or relays which require special protection. Use of surge arresters and capacitors for generator protection is discussed in Chapter 3.

In recognition of the susceptibility of electronic components to above-normal voltages and currents, manufacturer's data sheets normally specify limits for electronic components which must never be exceeded. Keeping the voltages and currents from coursing through the electronics of a

wind turbine during a lightning transient can be difficult. Damage to semiconductors from near or direct strikes has been documented at wind turbine sites [3]. Since damage to electronics can cause shutdown and economic loss, efforts to minimize this kind of lightning damage must be incorporated in the lightning protection of wind turbine design. Protection techniques for electronics are examined in Chapter 4.

The experience with lightning damage to aircraft is valuable when considering techniques to protect the turbine blades [7]. Details of blade protection techniques needed for metal, wood, fiberglass, and composites are described in Chapter 5. Chapter 5 also describes and discusses the results from simulated strikes to form a basis for blade protection recommendations.

Mechanical components such as bearings, gears, hinges, and hydraulic pumps can be damaged from lightning strikes. Lightning damage to bearings on large dish antennas has occurred when protection was not provided. The book, Lightning Protection of Aircraft [7], indicates flap hinges have received damage. However, reports in the literature are sparse in the area. Use of the recommendations in Chapter 5 will make the wind turbine less susceptible to mechanical component damage from lightning. It is unlikely that a wind turbine tower will be damaged from a lightning strike. Since some turbines could have composite, fiberglass, or even reinforced concrete towers, a few precautions taken during fabrication and/or construction would be worthwhile.

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Chapter 2

GROUNDING

2.1 INTRODUCTION

To better understand this and subsequent chapters an overview of lightning characteristics and lightning interaction with structures is provided. Based upon such interaction, the concept of grounding is broadened to include all structures that efficiently and safely conduct the lightning charge into the earth where it can be harmlessly dissipated.

2.2 LIGHTNING

From an electrical point of view, the negatively charged earth's surface and the net positively charged ionosphere comprise a giant capacitor. During fair weather, the capacitor creates a vertical potential gradient of about 100 volts per meter at the earth's surface. When a thunderstorm is overhead the polarity of the field reverses and potential gradients increase to several thousand volts per meter.

The total world capacitor discharge current averages approximately 1500 amperes through the imperfect insulator of the atmosphere. There are some 2000 thunderstorms in existence at any given time that regenerate the capacitor charge. Specifically, the cloud-to-ground lightning replenishes the earth's negative charge.

The above broad concept of this important consequence of lightning opens the door to many questions about the nature of the thunderstorm and the physics of lightning. However, most of the principles of lightning protection can be related to the characteristics of the lightning current waveform. Although lightning currents have been measured, the variability between flashes necessitates a statistical treatment when discussing the various parameters of concern (e.g. peak currents, rate of rise of current, number of strokes in a flash, etc.). This chapter focuses upon lightning characteristics and the relationship of these characteristics to grounding systems. Interested readers may consult any of the several excellent texts [1,2,3,4] to learn more about atmospheric electricity and lightning.

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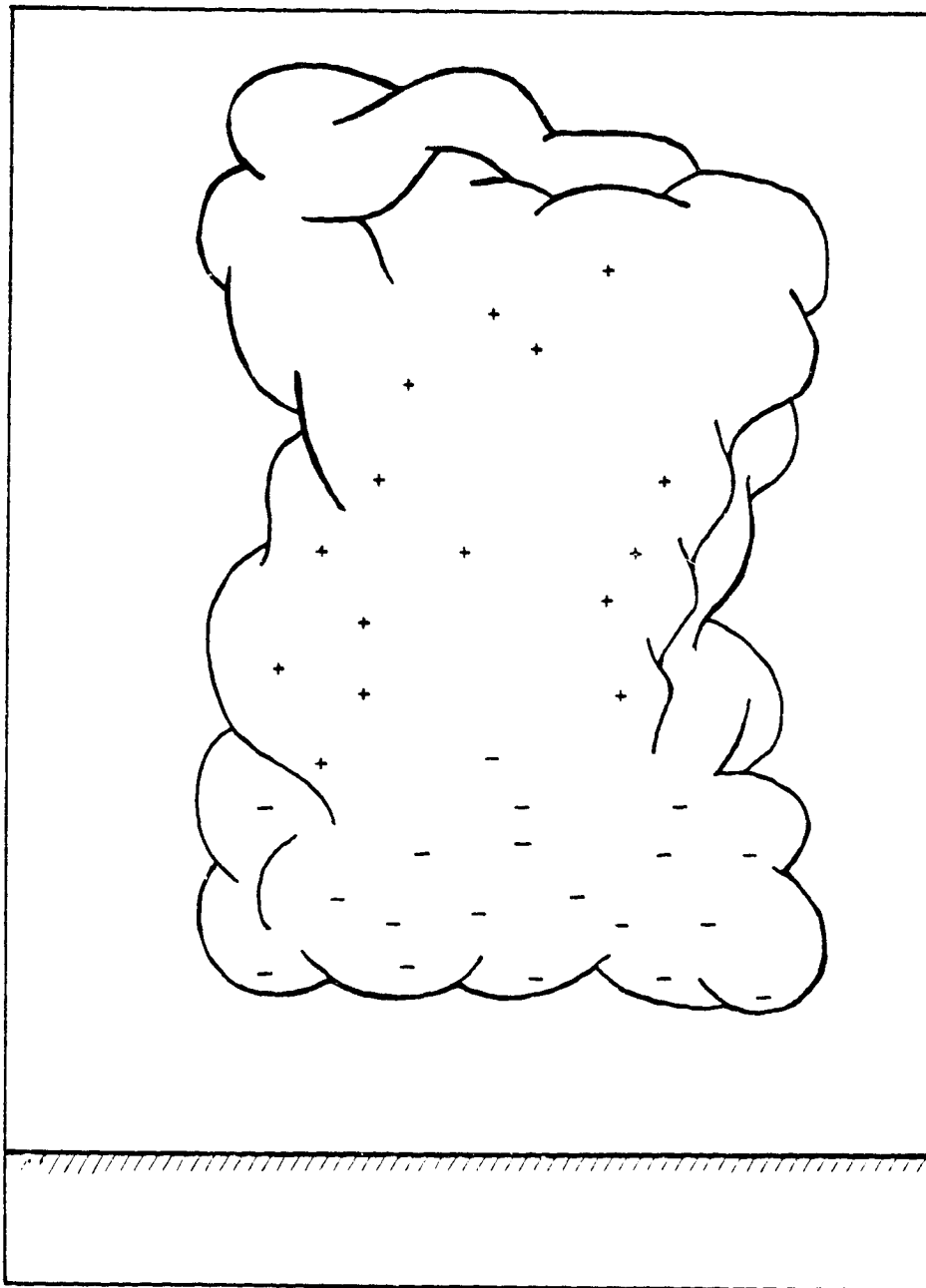


Figure 2.1: Model of a Thunderstorm Cell Above a Wind Turbine Site.

2.2.1 Lightning Characteristics

A model of a thunderstorm cell is shown in Figure 2.1. Typically, the vertical dimension is many times larger than the lateral width. The base of the cloud is negatively charged, causing an induced positive charge to accumulate on the nearby terrain. When the electric field reaches a critical value, an ionized discharge channel called a "leader" issues forth from the base of the cloud. In rapid succession "step leaders" (short extension of the leader) increase the length of the channel as it moves stepwise toward positive charges. If a step leader approaches the earth, it may be met by a streamer discharge from some point or structure on the earth's surface. Upon completion of the circuit, the rush of current, called the ground return stroke, illuminates and expands the ionized channel. This latter highly visible and energetic return stroke is what most people would consider "lightning". Such a cloud-to-ground lightning flash may contain several return strokes of diminishing current amplitude. A typical model of the lightning current is shown in Figure 2.2.

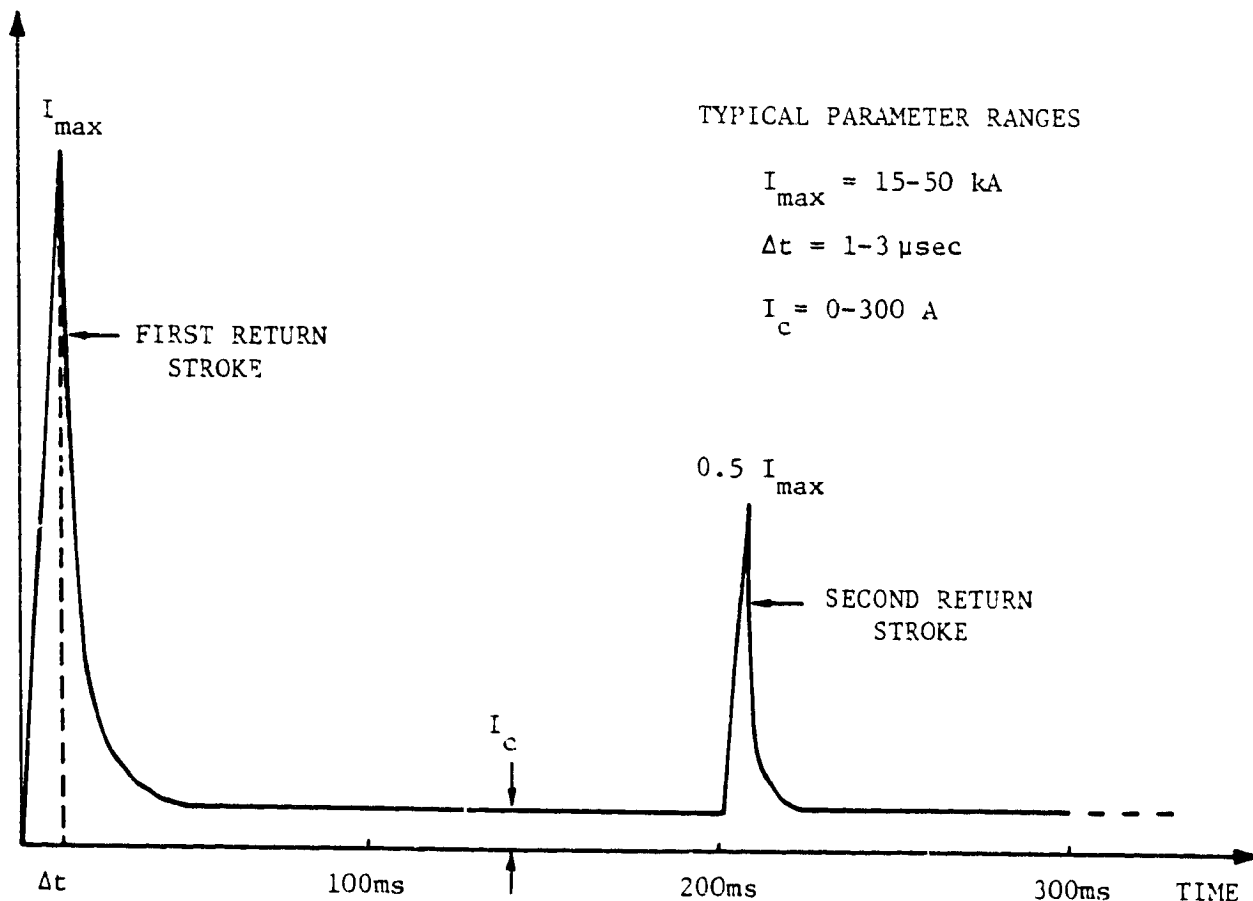


Figure 2.2: Model of Typical Lightning Current.

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There are several possible variations in lightning discharges, including the more common cloud-to-cloud discharge, and there are several lightning classifications (e.g. ball, ribbon, bead, etc.). Leaving further study of these to the academically curious, only one other type of discharge will be mentioned. Positive lightning flashes sometimes initiated by very tall structures or structures on very high terrain transfer positive charge to the earth. Such discharges may have peak currents exceeding 100,000 amperes.

As might be expected, there are significant variations in lightning parameters, though most cloud-to-earth discharges release more than 100 million joules of energy. A typical flash has sufficient energy to melt almost a ton of copper. Fortunately, much of the energy dissipation is associated with the physical phenomena of the discharge channel. Figure 2.3 [5] illustrates the variability in discharge current, and Figure 2.4 [5] illustrates the variability of the rate of rise of the lightning current waveform shown in Figure 2.2. For both figures the abscissa indicates the percent of lightning flashes that will yield a given peak first or second return stroke current or a given rise time. For example, Figure 2.3 indicates that about 5% of all lightning flashes could exceed a maximum peak current of 100,000 amperes.

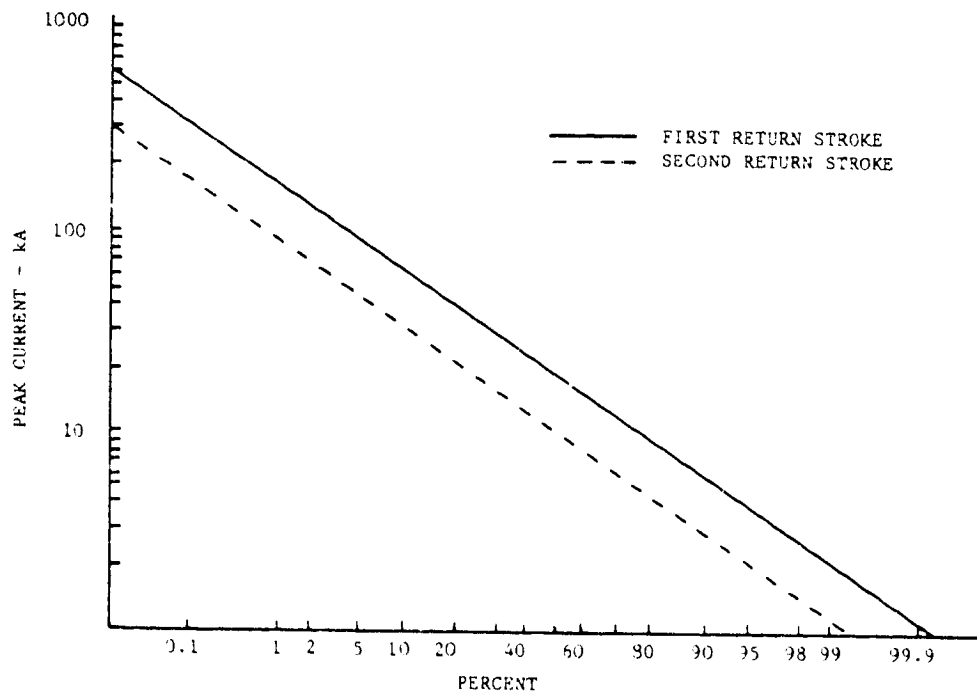


Figure 2.3: Distribution of Peak Currents
for Return Stroke and Subsequent Strokes.

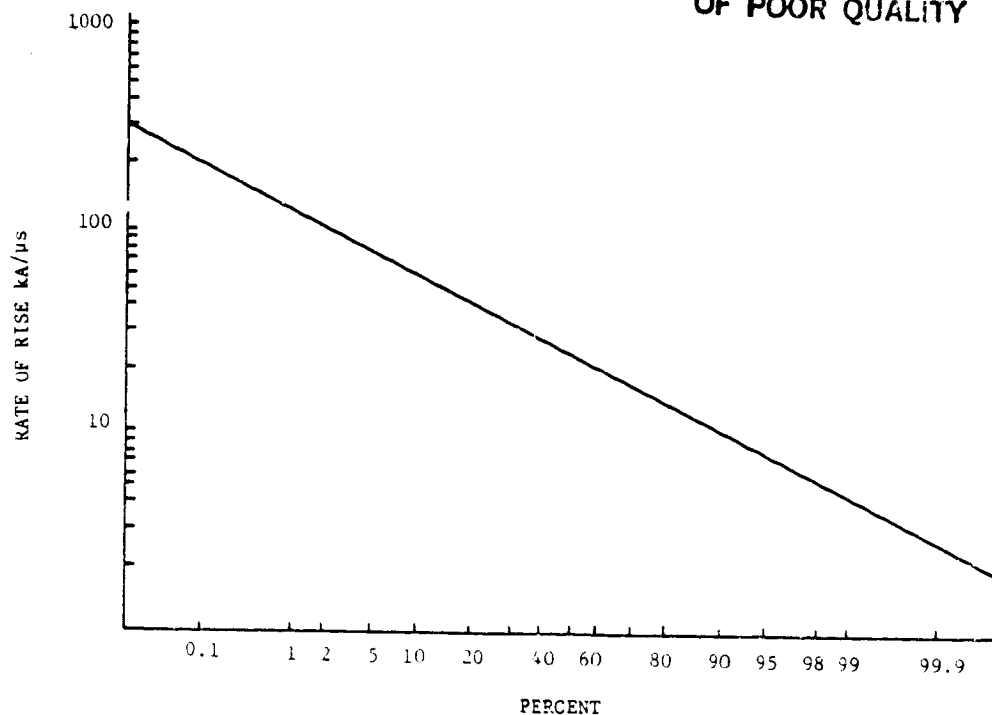


Figure 2.4: Distribution of Rates of Rise.

2.2.2 Strikes to Structures

Most likely lightning attachment points are blades, air terminals (lightning rods), the nacelle, or protuberances near the top of the structure. Upon being hit, the entire structure becomes a part of the lightning discharge path. From the attachment point to the ground the lightning current will flow predominantly through the lowest-impedance paths available. See Section 2.3.2.1.

In addition to direct strikes to the structure, nearby lightning flashes and other sources of electromagnetic impulses can induce currents and voltages sufficient to damage vulnerable electronic components. Such external threats may produce, along the wind turbine structure, electric fields that exceed 100,000 volts per meter, whereas a few volts above normal operating voltages can destroy many electronic components.

Although these indirect threats pose some special protection problems, a grounding system designed to accommodate direct strikes best serves all transient protection needs. Accordingly, unless otherwise stated, all comments in this chapter refer to direct strikes to the wind turbine

structure.

2.2.2.1 Probability of Lightning Strikes

The calculation of strike probabilities for a given structure is not an exact science. Such a conclusion is not surprising given the nature of the variables; e.g. local weather patterns, the nature of the terrain on which the structure is located, the percentage of lightning flashes that reach the ground, and the nature of the structure itself. Nonetheless, the simplified procedure described below often yields acceptable estimates. The average number of direct strikes to the turbine per year can be calculated from:

$$S = 4 \cdot 10^{-6} KTh^2 \text{ (strikes per year)}$$

where:

- S is the average number of direct strikes per year,
- K is the correction factor dependent upon local terrain,
- T is the number of thunderstorm days per year as read from the isokeraunic map in Figure 1.1, and
- h is the height of the tallest part of the wind turbine (normally the blade) in meters.

The above approximate formula is based upon adaption of data of Muller-Hillerbrand [6], Cianos and Pierce [5], and Golde [1]. See Figure 2.5. These data are most applicable to a temperate climate such as that of the United States. The correction factor, K, is included in the above empirical formula to account for local variations in the number of strikes per year. Local topology, ground cover, wind patterns, etc., appear to have some effect on the density of strikes at a given location. Certainly the location of a turbine on a small isolated hill would logically increase the probability of a direct strike because such a location would increase the effective height. In the absence of observations by trained personnel, K would be omitted from the strike equation (i.e. K set equal to one). Trained observers may include personnel associated with weather stations, communications towers and antennas, universities, and power companies.

2.2.2.2 Lightning Interaction with Structures

The exact paths taken by the lightning current depend upon the attachment point and the relative impedances of the paths. Steel structures tend to be symmetrical, so current should be distributed equally among the legs or about the structure body. Critical points in the path(s) may include bearings, enclosures, or wires for electrical or electronic systems, and the connecting points to the grounding system. Nonconducting structures should be protected by air terminals and down conductors which are attached to an

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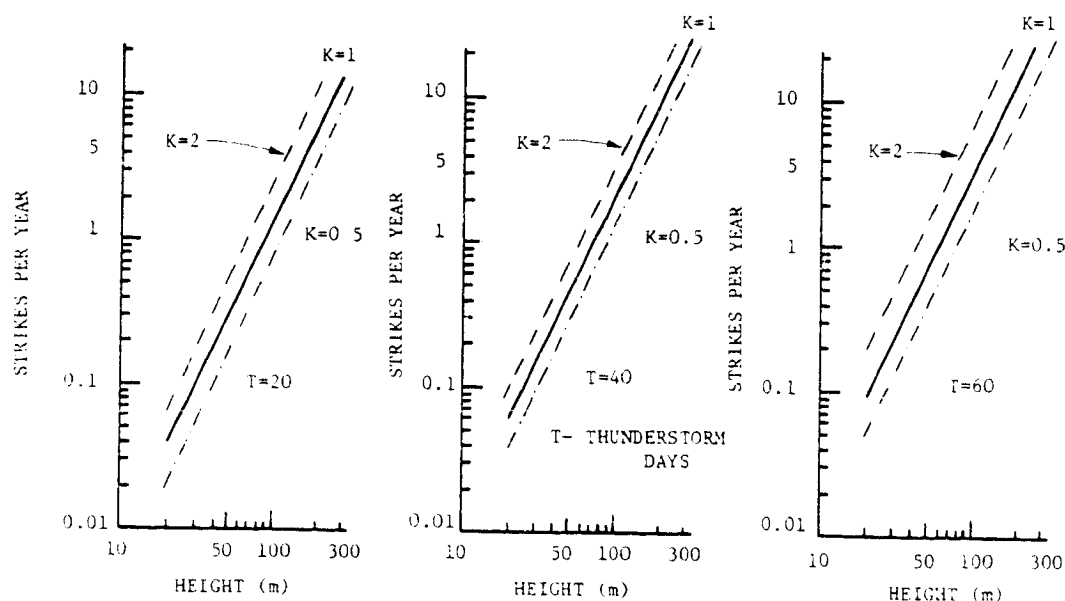


Figure 2.5: Approximate Number of Direct Strikes to Tail Structures.

appropriate grounding system (see Section 2.4). Vertical-axis wind turbines employ guy wires which carry lightning current to ground. For conducting towers with cross members between legs, for conducting solid towers, or for down conductors separated by several meters, the inductance per unit length of the tower or down conductor may be calculated from the approximate formula [7]:

$$L = 0.2 * \ln(1000/r) \quad (\text{microhenries per meter})$$

where:

r = the average radius of the tower or down conductor in meters.

For such conducting structures the resistance of the tower may be neglected, so that the voltage per meter length is:

$$v = L \, di/dt.$$

In this equation, L is the inductance calculated from the previous formula and i is the lightning current (see Figure 2.2 for i and Figure 2.4 for di/dt).

For all-metal towers, the inductance per unit length is relatively insensitive to the tower diameter. For example, tower diameters in the broad range between 3 and 12 meters produce inductances in the narrow range between 1 and 1.3 microhenries per meter. Even for a worst-case condition (see Recommendation 5 Section 2.4.1) of a single down conductor of radius 1 cm the inductance increases to only 2.3 microhenries per meter. Using current rate-of-change extremes of 10 kA/microsecond (relatively benign) and 200 kA/microsecond (relatively severe), the peak electric fields along the tower will vary from 10,000 volts per meter to 460,000 volts per meter for the low and high extremes with the combinations of v , L , and di/dt considered above. Thus, a 100 meter tower could experience peak potentials, at the tower top, of 1 to 46 million volts with respect to ground. Obviously, the higher field values would be sufficient to cause insulation failures, flashovers and hazards for humans. High-resistance grounds, corroded or poor connections to the ground system, and non-straight-line down conductor paths increase the probability of breakdown (flashovers) between the tower and buildings/personnel/livestock/objects near the tower.

The factor which contributes to larger than expected instantaneous currents and voltages is the surge performance. When lightning strikes a given point on the tower structure, voltage and current wavefronts (surges) propagate along the structure. Hence, the structure becomes a transmission line which causes reflections whenever the surge encounters any discontinuity in impedance of the line. For a wind turbine, the important and controllable discontinuity points are: (a) the points of connection of the tower lightning paths to the ground system, and (b) the end points of the in-ground system. A high-resistance ground system or a non-grounded tower will result in a reflected voltage wave that adds to the incident wave and increases the possibility of sideflashes and insulation flashovers. Conversely, a low-resistance ground causes a reflected voltage wave of polarity opposite of that of the incident wave thereby reducing these dangers.

2.3 GROUNDING FUNDAMENTALS

The following sections address the fundamental principles to be employed in the design of an effective grounding system.

2.3.1 Purposes of Grounding

2.3.1.1 Lightning Protection

The 1980 National Fire Protection Association (NFPA) lightning protection code [8] includes a risk index formula based upon six criteria:

1. Type of structure,

2. Type of construction,
3. Relative location,
4. Topography,
5. Occupancy and contents, and
6. Lightning frequency.

Five risk classifications, ranging from light to severe, are given for guidance of anyone responsible for designing lightning protection systems. Based upon the given formula, most wind turbines are assessed in the severe risk category. For this reason and the high cost associated with add-on grounding construction, lightning protection should be incorporated into the original design and construction.

The primary goal of lightning protection is to transfer the lightning flash energy into the ground with a minimum amount of damage to the wind turbine. The lightning current paths, whether integral parts of the turbine structure or special down conductors, should provide protection:

1. for critical mechanical parts (e.g. bearings),
2. against insulation flashovers,
3. against thermal and fire damage,
4. for power equipment and electronics, and
5. for personnel/livestock and secondary structures in close proximity.

As will be discussed in detail in the following sections, damage is minimized by low-impedance paths to ground and by low-resistance ground systems which dissipate the energy harmlessly in the earth.

2.3.1.2 Fault Protection

Any power circuit failure, which interferes with the normal flow of current, is termed a fault. Most often lightning will create an ionized path from a point in the power circuit to ground. Current provided by the power source(s) will flow through this low-impedance ionized path (sometimes called a short circuit). Whenever the sources maintain the ionized path after lightning current has ceased, a device called a circuit breaker is employed to interrupt the current flow and to extinguish the ionized channel.

The function of the ground system is to accommodate any fault current possible, whether caused by lightning, insulation failure, or by other conditions. The worst-case generator fault current can be calculated from the turbine generator name-plate information. The worst-case current is the generator short-circuit current. Conductors designed to carry the short-circuit current are generally sufficiently large (No. 8 AWG or larger) to carry any lightning transient.

2.3.1.3 Personnel Safety

Personnel or livestock at the turbine site are in considerable danger during an electrical storm. The safest procedure for personnel is to vacate the site. The site should be fenced to exclude livestock. Absolute safety for personnel at the turbine site during a lightning flash cannot be assured.

A person touching any conducting part of the structure during a lightning strike will develop a potential (touch potential) between his feet and the touch point. Should the insulation between his feet and any conducting part of the structure (or ground) not be sufficient to prevent arcing, a current will flow from the touch point to the feet. See Figure 2.6. Current flow through the body can cause the heart to cease functioning properly and/or respiratory paralysis.

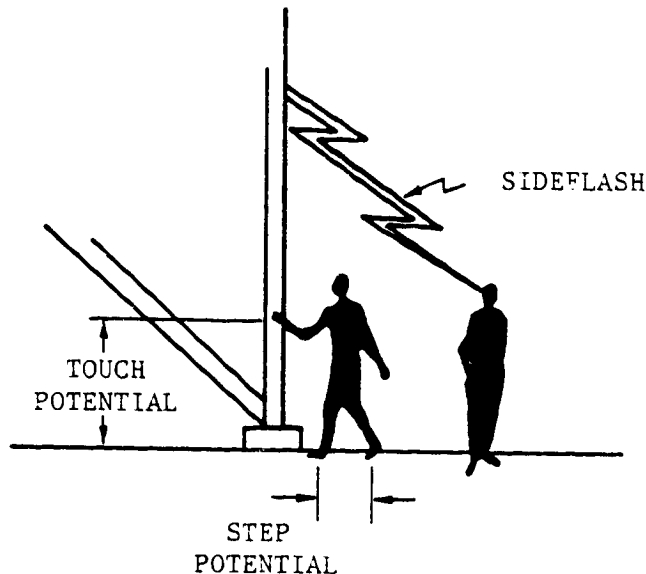


Figure 2.6: Step and Touch Potentials and Sideflash.

A person standing on the ground (or floor) will develop a potential (step potential) between the two feet. Again, insufficient insulation could permit enough current to flow to constitute a dangerous situation. The most hazardous step-potential location is near but outside of the base of the structure. A person standing several feet from the tower is in much less danger than one standing one foot from the tower base. Nonetheless, personnel or livestock standing near a tower at the instant of a direct strike to the tower may be injured or killed by a sideflash if the tower is not properly grounded (see Section 2.2.2.2).

The above hazards can be reduced by a low-resistance earth-ground system, well-insulated shoes, and insulated mats. At power substations, a 3 to 4 inch mat layer of crushed rock is often used. When the crushed rock surface layer has much higher resistivity than the ground beneath it, body current due to the step potential can be greatly reduced [9]. Such a surface layer serves a second function of retarding evaporation of moisture from the earth. Moist earth exhibits a much lower resistivity than dry earth.

Section 2.3.2.4 discusses methods of obtaining "safe" ground grid systems. The common denominators for defining "safety" are the step and touch potentials. Although the factors involved in determining the lethal threshold currents for humans are highly variable and statistical in nature, the power industry seems to use consistently a number of standard assumptions that apparently provide values that are safe.

The IEEE Standard 80-1976 [9] provides an excellent discussion of step and touch potential assumptions and methods of calculating safe values. This standard cites research by C.F. Dalziel who concludes that 99.5 percent of all persons should withstand, without ventricular fibrillation, current determined by the equation:

$$\int i^2 dt \leq 0.0135$$

from which $i = 0.116(t)^{-1/2}$ amperes,

where:

i is the rms current through the body, in amperes,

t is the time duration of shock, in seconds,

and

0.0135 is an empirically derived "energy constant".

The same publication assumes the body resistance to be 1000 ohms for both touch and step potential calculations. The foot span associated with the step potential is assumed to be one meter.

The calculation of step potentials within the bounds of the ground grid are somewhat cumbersome [9,26,28] unless a computer is employed. However, in the unprotected region beyond the ground system boundary, the approximate step potential may be calculated from the expression [1]:

$$V_{\text{step}} = \frac{i \cdot s}{2 \pi d(d+s)}$$

where:

V_{step} is the potential in volts, ρ is the earth resistivity in ohm-meters, s is the step length in meters, and d is the distance in meters between the center of the turbine tower and the person's leg nearest the tower. This expression assumes a circular ground system and a uniform earth resistivity.

Researchers continue to publish articles [10,11] relevant to these calculations. Consulting current literature for new developments before finalizing any design is recommended.

2.3.1.4 Reference Points for System Grounds

For most people, including many electrical engineers, the terms ground, common, earth ground, system ground, chassis ground, effectively grounded, resistance grounded, reactance grounded, etc. [19] are confusing.

For power engineers, the reference point for the system ground is normally located at the source and is a direct connection to earth, where possible. See NEC article 250 in Reference 12. However, the reference point for an electronic signal is a much more critical and ambiguous concept for communications, control, and data processing engineers. When the signal reference points of communicating systems are at slightly different potentials due to a ground current flow, the exchanged signal may be misinterpreted.

During a lightning flash to any tall structure, the potential difference between reference points of some communicating systems may reach millions of volts. In such cases, the only options available to the systems designers may be to minimize physical damage and to minimize the consequence of misinterpreted signals. These situations are discussed in Chapter 4.

There are techniques and procedures which can reduce, and in some cases avoid, such worst-case situations. Physically locating critical communicating systems close to one another is a simple but powerful means of reducing harmful potentials between system and chassis grounds. The techniques of potential equalization and magnetic coupling minimization as discussed below are powerful tools as well. Also, see Chapter 4.

2.3.2 Factors in Effectively Grounding Lightning

The following sections elaborate on these factors to be considered in the design of grounding systems:

- o Current Diversion and Magnetic Coupling

- o Potential Equalization
- o Shielding and Bonding
- o Earth Connections and Ground Grids
- o Earth Electrical Behavior

2.3.2.1 Current Diversion and Magnetic Coupling

One objective of lightning protection is to divert the lightning current through low-impedance, non-critical paths to ground. The lightning-protection designer should minimize high-current paths near enclosures that contain sensitive components.

For most larger horizontal-axis machines, the supporting steel tower structure provides the lowest-impedance path to ground. With most of the current flowing along the outer extremities of the tower, the magnetic fields inside the structure are greatly reduced. For nonconducting towers, a minimum of at least three down conductors equally-spaced about the periphery of the cross-section of the tower should be used.

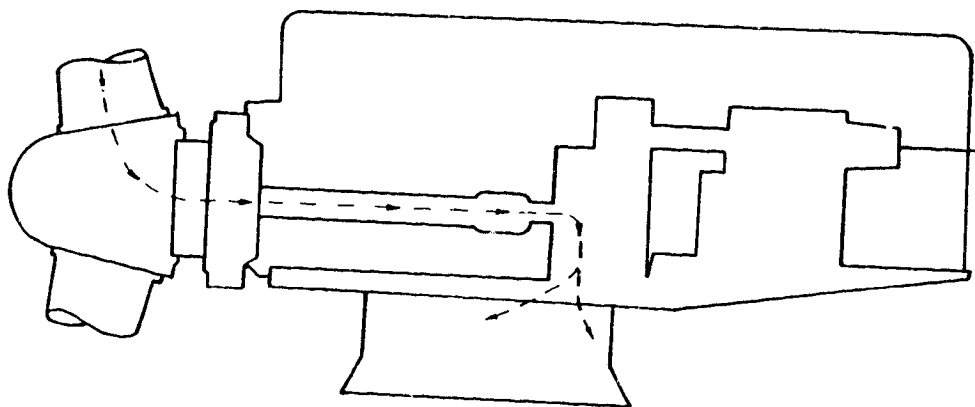
Additional equally-spaced down conductors will further reduce the magnetic coupling inside the tower if they share the lightning current. Sharing is accomplished by common connections. Particularly critical are the common connections near the top of the tower. Such connections should be made at a natural equipotential surface. For tall structures these surfaces should be horizontal planes. See Section 2.3.2.2 and Figure 2.8.

Vertical-axis wind turbines may have guy wires that can share the lightning current discharge. Thus, having good conducting connections to these wires at the top of the turbine and to low-resistance grounds at the earth anchor points is very important. Nonetheless, current can flow directly down the shaft or through the blade structures. If bearings exist in the flow path, current diversion through shunt conductors may provide sufficient protection for vulnerable parts. Brushes at one end of the shunt conductors must be provided to accommodate relative motion between moving parts. There is negligible value in adding guy wires, beyond mechanical needs, for the purpose of diverting current from the main shaft. Approximately one third of the total current will flow down the main vertical shaft regardless of how many guy wires are used.

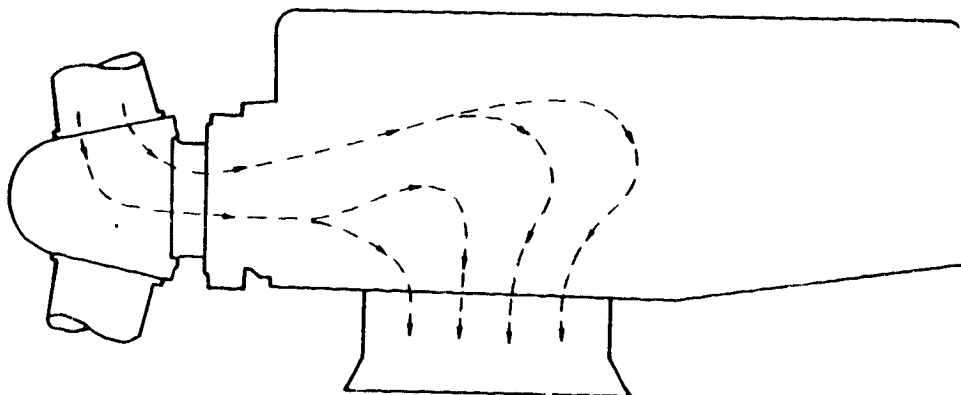
The minimization of magnetic fields inside the tower is particularly important for the protection of exposed wires, cables, and electronic systems. Self-supporting trussed structures often employ tubular tower legs in which cables and wires may be placed to shield them from the magnetic fields. Completely-enclosed tubular steel towers would exclude all magnetic fields if there were no openings or unshielded cable entries. See Chapter 4.

For horizontal-axis turbines the entire nacelle normally rotates on bearings located at the top of the tower. If unlimited rotation is allowed, the power/controls/communications cables in the nacelle must be connected to cables in the tower through slip rings. To divert lightning currents away from the bearings and slip rings, it is necessary to employ a spark-gap skirt of low inductance or shunts with brushes as described above. Even with such protection, a fraction of the current will flow through the bearings and slip rings.

The possibility of omitting the nacelle shroud or of employing composite (nonconducting) materials for the construction of the nacelle helps to illustrate the concept of current diversion. Figure 2.7(a) illustrates current flow down the blade through the hub, shaft, generator, and bedplate to the top of the supporting tower. Of course, the current will follow the paths of least impedance. This means the current will tend to spread out to the external surfaces of the metal. This reasoning follows the concept of skin effect or internal inductance which is articulated in most electromagnetic textbooks [13,14].



(a) NONCONDUCTING NACELLE



(b) CONDUCTING NACELLE

Figure 2.7: Lightning Current Paths in Nacelle.

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Given the same configuration, except that the nacelle is assumed to be made of metal, the preferred current path will be over the surface of the nacelle to the tower. See Figure 2.7(b).

2.3.2.2 Potential Equalization

Potential equalization is a key concept in lightning protection. Ideally, the wind turbine designer should locate all vulnerable components, communicating systems, and personnel so that their immediate surroundings (or systems with which they are in contact) are at the same potential. The difficulty with achieving the ideal can best be grasped by referring to Figure 2.8.

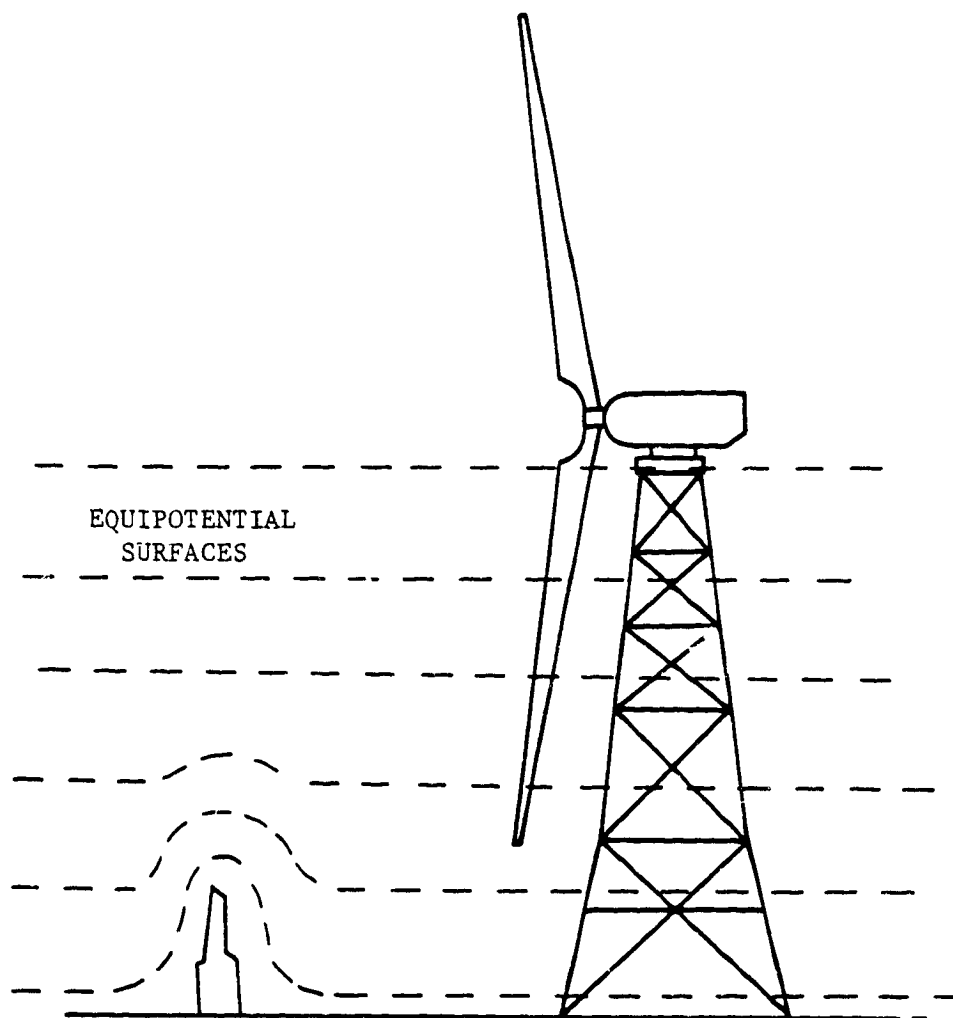


Figure 2.8: Voltage Excursions
on and around Tower at One Instant During Direct Lightning Strike.
(dotted lines represent equipotential surfaces)

For this case of symmetrical voltage distribution, it is obvious that entities only at the same elevation would be at the same potential. When any object, (such as the grounded structure in Figure 2.8) is physically connected at any given level, a local distortion of potential distribution will occur. The resulting increase in electric field may cause flashovers, arcs, or insulation breakdown. Where systems at different levels are linked by conductors, a current will flow between them. The magnitude of this current will be the instantaneous difference in potential between the two locations divided by the impedance of the interconnecting conductor.

To minimize lightning damage to diverse systems that are distributed over a finite area at different elevations, the tree concept is a valuable aid in making decisions about local ground-path connections (see Figure 2.9). In general, the designer responsible for lightning protection should attempt to connect systems, shields, and machinery that exist at the same level and that are physically nearby. This process continues downwards, until the earth ground is reached.

Thus, a lightning flash to one of the branches will tend to flow through the path of lowest impedance to ground, endangering the fewest number of subsystems. The interconnection of blocks from different branches can cause ground loops that may increase vulnerability of some of the systems.

Any system or component that is electrically insulated from others (see box at top of Figure 2.9) but in the lightning path will simply provide a short conducting path, then a jumping-off point for the lightning channel to some nearby component.

2.3.2.3 Shielding and Bonding

Shielding and bonding are techniques used to divert current from paths that include vulnerable systems or components. A conducting nacelle, an enclosed steel tower, and the switch gear panel enclosures are all forms of shields which may be used to reduce exposure of their internal systems to hazardous voltages and currents. The principles discussed in the previous section are applicable to the locations of both shields and bonds. Details of shielding methods and design are covered in Chapter 4. For details of acceptable bonds for a wide range of applications consult The National Electric Code Handbook 1981 [12] and other applicable codes.

Of great concern are the practical problems associated with poor connections whether caused by improper installation or corrosion. Denny, et al., [15] address these topics in great detail. Poor electrical bonds in the lightning path can cause large voltages to appear between interconnected systems. The lightning current may simply jump the poor connection causing no harm; or the created voltages may endanger life; or a new path may be created by the channel passing to a nearby, and perhaps more vulnerable component.

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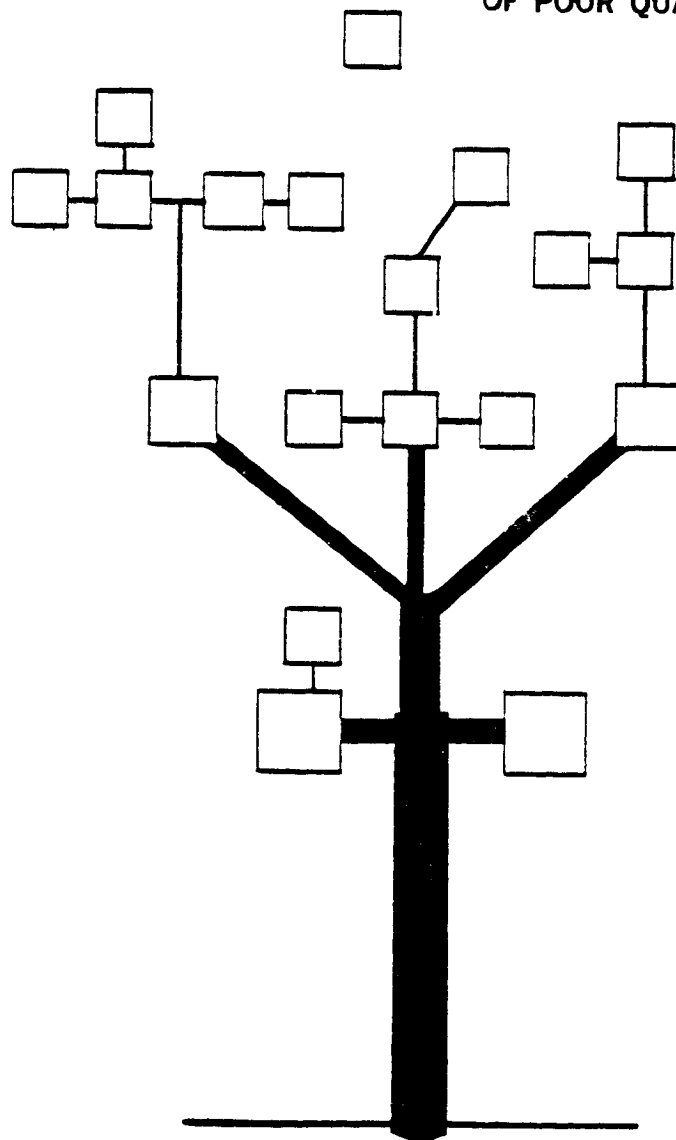


Figure 2.9: Illustration of the Tree Concept.
(boxes represent components or subsystems)

2.3.2.4 Earth Connections and Ground Grids

A low-resistance earth ground is desirable because it reduces the touch and step potentials described in Section 2.2.1.3. Furthermore, a low earth resistance reduces the maximum voltages along the tower to help protect electronics and other components. The initial lightning pulse proceeds down the tower in much the same fashion as a pulse travels down a transmission line. If such a pulse encounters an open-circuit termination (by analogy an ungrounded or very-high-resistance ground), a voltage wave of the same magnitude is reflected back toward the source essentially doubling the

voltages per unit length. Such a situation on a wind turbine promotes insulation breakdown, flashovers, and danger to humans.

On the other hand, a short-circuit or very-low-resistance termination will cause a reflected voltage wave of opposite polarity of the incident wave thereby reducing the voltage drop along the line (or tower) to near zero. This desirable condition is not attained without some trade-off. Since the voltage pulse is accompanied by a current pulse, currents and voltages induced through magnetic coupling will be increased with a low-resistance ground.

The nature of the wind forces on a wind turbine requires a tower base of considerable mechanical strength. Because concrete behaves electrically very much like earth, such a base is conducive to the design of an effective lightning path to the earth. It is very important to incorporate the design of the electrical ground system into the initial design of the tower base/pad/foundations/piers/footing/rock anchors, etc. These structures extend into the earth, and they require reinforcing bars that can also serve the purpose of conducting lightning current to ground. There are a number of communication and power transmission line tower foundations in existence that were designed to serve the suggested dual function.

Normally, the tower load is transmitted through steel baseplates to a concrete foundation or appropriate footing. The baseplates are attached with anchor bolts which extend into the concrete and which can be connected electrically to parts of the reinforcing bar system. When the steel reinforcing bar system is utilized as a portion of the ground electrode, the electrical connections between the tower (or other down conductors) and the ground electrode are most critical. The connection must be welded or an approved mechanical-electrical connection [12,15].

Inside the concrete, the reinforcing bar to which the tower/down conductors are solidly connected should be as long as practical, and it should be in contact with a large number of other bars. It is strongly recommended that additional approved bonds be made until the accumulated length of solidly connected bars extends at least twenty feet [12]. This recommendation applies to each of the ground-electrode connections which normally number three or four. Many other reinforcing bars should be in physical contact with the solidly-connected bar by physically laying across it or by physically tying bars together with tie wires. In Figure 2.10 the solidly-connected electrode is shown in black. The desired net effect is to have the entire reinforcing bar network act as a single three-dimensional ground grid. A very large surface area of the ground electrode insures low fault or lightning current densities so as to minimize breakdown and thermal damage.

In addition to the portion of the ground electrode formed by the reinforcing bars in the tower footing, it is standard practice to bury one or more conducting rings just outside the foundation in the soil. These rings serve:

1. to guarantee equipotential earth around the tower base,

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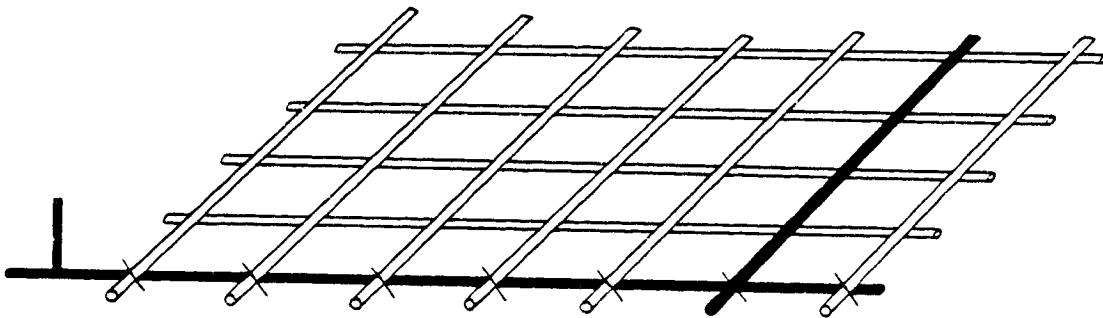


Figure 2.10: Use of Concrete Reinforcing Bars as the Earth Electrode.

2. to reduce touch and step potentials at tower base,
3. to reduce the hazards of sideflashes,
4. to provide lightning breakdown paths in soil rather than in the concrete or along the earth's surface, and
5. to provide accessibility to the outer edge of the ground system.

Accessibility is important whenever further reduction in ground resistance is needed after site completion.

Because wind turbine sites are often in rocky or dry high-resistivity locations, counterpoises attached to the outer ring generally provide the most practical means of obtaining the desired ground-electrode resistance. Counterpoises are simply radially buried wires that can be extended to the length needed to reduce the ground resistance. For very rocky terrain, counterpoises are sometimes laid on top of the ground. See Figure 2.11 for a complete ground system.

Ground resistance may be lowered by connecting the ground system to other non-dangerous conducting entities such as metal water lines or well casings (connections should never be made to gas or oil pipelines).

It should be noted that indiscriminate connections can cause problems. One of the problems is that of corrosion due to electrochemical effects. If different parts of the ground system contain metals of different electrochemical potentials a battery will be formed. The more electronegative metal will act as the cathode, and ions will be transferred through the damp earth or concrete, acting as the electrolyte, to the anode metal. Even with single-metal systems, battery-type currents can exist where electrolyte concentrations vary with positions in the soil in which the ground system is buried.

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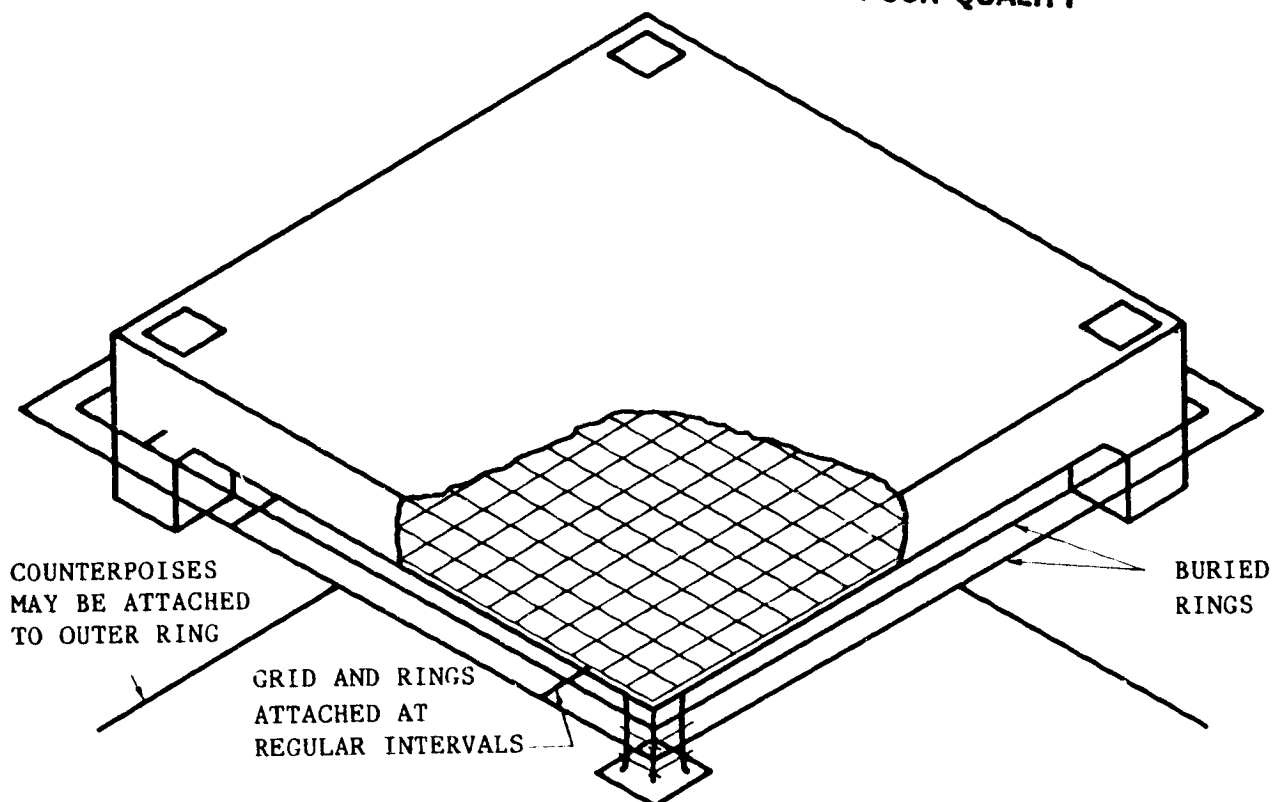


Figure 2.11: Ground System
Consisting of Reinforcing Bars, Rings, and Counterpoises.

For the recommended ground system described above, the most practical arrangement might be one in which the outer rings and counterpoises would be large stranded copper connected to the reinforcing steel rods. This design choice illustrates a typical trade-off situation. Stranded copper is employed in the soil because it is much easier to shape and it corrodes less than 25% as fast as steel. Because stranded conductors have a large surface area exposed to corrosion, some countries (not including the USA) do not permit its use for underground lightning electrodes. For this reason, stranded wire should be large (e.g. 300 MCM, 12 strands).

Once such a choice has been made, it becomes necessary to calculate the amount of electrolytic damage that might occur. This can be done by employing Faraday's law:

$$W = QA/Fn$$

where W is the weight in grams of material transferred, A is the atomic weight of the transferred cathode material, Q is the charge obtained by multiplying current in amperes by time in seconds, F = 96,500 coulombs per mole, and n is

the valence of the ion. For the example above, the current, I , is calculated from the electrochemical potential difference divided by the resistance of the earth, R_b , between the two parts of the system ground composed of the steel reinforcing bars and the copper rings or counterpoises. The electrode potentials (sometimes referred to as galvanic or electrochemical potentials) of several metals are shown in Table 2.1.

TABLE 2.1
Galvanic Potentials of Metals

<u>Metal</u>	<u>Relative Potential</u> (V)
Magnesium and its alloys	-1.6
Zinc diecasting	-1.1
Zinc plating on steel	-1.05
Chromate-passivated and galvanized iron	-1.05
Cadmium and cadmium plating on steel	-0.80
Wrought aluminium	-0.75
Non-corrosion-resisting steel or iron	-0.70
Cast iron	-0.70
Duralumin	-0.60
Lead	-0.55
Lead-silver solder (2.5% silver)	-0.50
Terne plate	-0.50
Tin plate	-0.50
Tin-lead solders	-0.50
Chromium plating, 0.0005 in. on steel	-0.50
Chromium plating, 0.003 in. on nickel-plated steel	-0.45
Corrosion-resisting steel (12% chromium)	-0.45
Tin-plating on steel	-0.45
High-chromium steel, 18/2	-0.35
High-chromium steel, 18/8	-0.20
Brasses	-0.25
Copper and its alloys	-0.25
Nickel-copper alloys	-0.25
Nickel plating on steel	-0.15
Carbon (colloidal graphite in acetone, evaporated to dryness)	+0.10

For the copper-iron case, $I = [-0.25 - (-0.70)]/R_b$. During wet periods or for low-resistivity soils, it is possible for R_b to be as low as one ohm. For such a case, the iron transfer rate could amount to several kilograms per

year. The outer steel rods in closest proximity to the copper rings would be affected most.

Observers [12] report that corrosion rates will actually be less, often considerably less, than values calculated as above due to ameliorating factors. These factors include coatings that naturally accumulate on the electrodes in contact with earth or concrete. Such coatings increase the effective electrolyte resistance, thus lowering the current flow.

For ground system designers in the process of developing a standard (i.e. for a wind farm or farms), the performance of both calculations and measurements on a prototype is an advisable procedure. To perform tests to determine R_b on the current flow, it is necessary to provide for a means of physically disconnecting the two portions of the circuit that are constructed of different materials. Such tests should be conducted after concrete has cured and the ground has settled. To obtain the worst-case condition (largest loss of electrode material), a measurement should be performed when the ground has a high moisture content.

In the event that the projected damage is too large, corrective action should be taken. Corrective action includes the alternatives of :

- a) replacing the ring/counterpoise system with a metal which has an electrochemical potential close to that of the reinforcing bars, and
- b) installing a sacrificial electrode [1] that is more electronegative than the cathode material (reinforcing bars).

The viability of method (a) depends upon matching chemical potentials with a metal that is rust resistant. The viability of method (b) depends upon the sacrificial electrode having a potential which is more negative than the cathode material by a magnitude approximately that of the difference between the anode and the cathode. Because the sacrificial electrode is eaten away, it must be periodically replaced.

Heretofore, the discussion has alluded to the resistance of the ground electrode rather than the impedance. For 60 hertz faults there is little difference between the two quantities. But lightning is a transient phenomenon encompassing many frequencies. How should the load impedance of the ground be modelled for a lightning flash?

This question has been addressed by a number of researchers [16,17,18]. These researchers define a surge impedance as the ratio of the instantaneous voltage divided by the instantaneous current into the ground electrode. Thus, the surge impedance is useful in determining the reflected wave on the tower due to the ground system as its load. The surge impedance varies with time in the fashion shown in Figure 2.12.

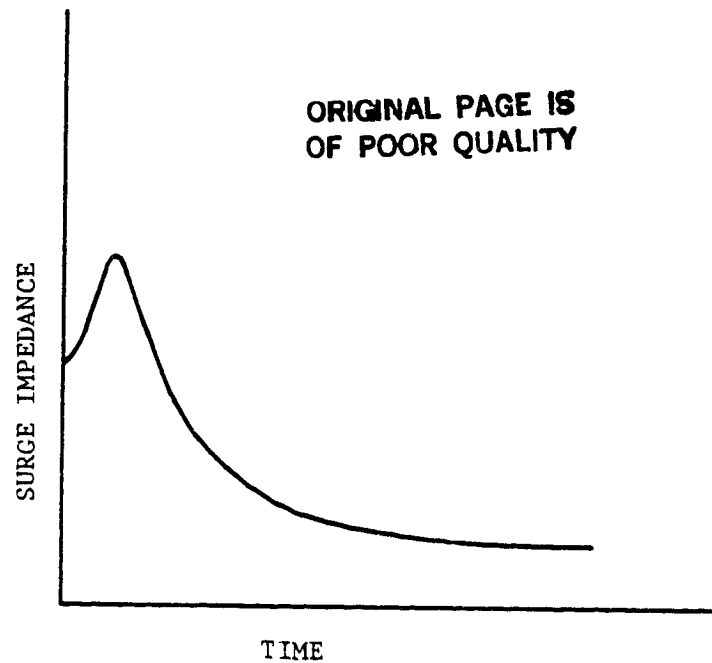


Figure 2.12: Surge Impedance as a Function of Time.

Even though the surge impedance varies as shown, estimated reflection values that assume a load impedance equal to the dc ground resistance are generally sufficient for most purposes.

2.3.2.5 Earth Electrical Behavior

The earth's crust is a non-homogeneous, anisotropic, nonlinear and layered medium. Its electrical behavior is a function of these different characteristics as well as moisture content, chemical composition, frequency, temperature, and pressure. Furthermore, characteristics and conditions often vary markedly between sites.

So, how does the designer responsible for the electrical ground system cope with such a complex medium? The answer may be better understood by comparing the two extreme conditions of an ungrounded tower and a tower with an infinite ground system.

Just prior to the lightning flash a large volume of negative charge in the cloud induces a similar positive surface charge several square kilometers in extent on the earth's surface. The ionized channel to earth provides a path for the electrons to reach the earth. If it is assumed that the lightning channel terminates on a wind turbine tower, what happens as the electrons reach the earth and spread out to neutralize the positive surface charge? Consider first the case of an ungrounded tower.

At the point of electron injection, the resistance between the tower base and other distant points is very large regardless of the electrical properties at the site. In fact, the IR voltage will exceed the breakdown strength of the earth and one or more types of breakdown will occur. These include breakdown in the volume of soil beneath the injection point, breakdown of the air (sideflash) between the tower and a radial point beside the tower, and breakdown along surface paths on top of the ground. The latter two cases are recognized as extremely dangerous to humans, animals, and nearby structures.

This dangerous voltage (or more correctly, electric field strength) diminishes with distance from the injection point. The rate of decrease varies somewhere between inverse radius and logarithm of inverse radius depending upon several of the factors mentioned in previous paragraphs. At some radius, a point which is considered no longer dangerous will be reached.

At the other extreme, the earth's surface could be covered by a sheet of high-conductivity metal extending radially from the tower to the outer edge of the positive induced surface charge. This economically unrealistic system would shrink the danger point to essentially zero. It follows that providing a good ground system to the hypothetical point of danger transition is sufficient. Physical configurations for such a system are described in Section 2.3.2.4. The equations for determining this point are provided in Section 2.3.1.3.

A great deal of effort has been expended to increase the understanding of the earth's behavior. The resultant knowledge has been employed to find ground system resistance, inductance, capacitance, breakdown strengths, current densities, corrosion rates, etc.

For example, all formulas developed to find the resistance of the variously shaped ground electrodes show the resistance to be directly proportional to the earth's resistivity. This raises two questions. What method should be used to measure the resistivity which is used to calculate the electrode resistance? And, can the resistivity be altered to serve a given purpose?

Soil resistivity can be decreased by adding moisture and/or chemicals to the soil [1,19,20]. Except for some special applications, neither practice has gained acceptance as a practical means of obtaining a low ground-electrode resistance. To maintain a given moisture content, water must be supplied almost continuously, while chemicals tend to leach away and to cause pollution problems.

Resistivity can be measured indirectly. Measurement methods are described in IEEE Standards [21,22] and in current literature. The four-point probe method (see Figure 2.13) is considered the most accurate. Instruments designed specifically to measure resistivity are available (see buyer's guide or appropriate trade publications).

Four small electrodes are inserted into the earth to a depth "b" in a straight line spaced "a" equal distances apart. The electrodes are assumed to be insulated except at the tips. A current I is passed between the outer

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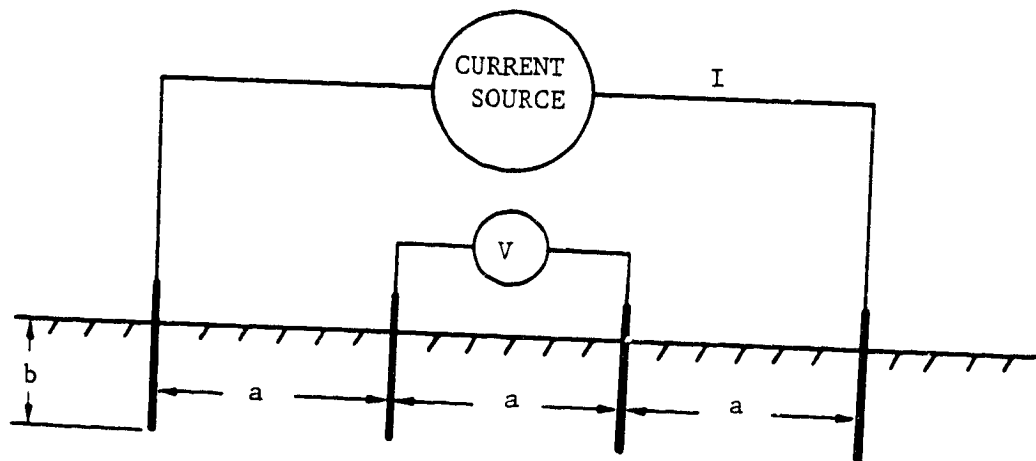


Figure 2.13: Four Point Probe Resistivity Test.

electrodes, and a potential difference V is measured between the inner electrodes. The ratio V/I is called the mutual resistance, R . The resistivity is then determined from the formula:

$$\rho = \frac{4\pi a R}{1 + \frac{2a}{(a^2 + 4b^2)^{1/2}} - \frac{a}{(a^2 + b^2)^{1/2}}}$$

where ρ has units of ohm-meters when length dimensions are in meters. For this model it is assumed that the earth is a homogeneous isotropic medium. When $b < 0.1a$ the equation reduces to $\rho = 2\pi a R$. Another method, the three-probe method, is widely used, particularly by test equipment manufacturers. Most equipment manufacturers furnish a manual which details several methods of measurement and discusses accuracy. However, because of the variability in weather factors and measurement accuracy, ground system designers may be quite satisfied with resistivity values within $\pm 100\%$ of the average value.

For guidance, IEEE guide [22] provides a very simple table attributed to Rudenberg. The table is reproduced as Table 2.2.

TABLE 2.2
Average Resistivity of the Ground

<u>Type of Ground</u>	<u>Resistivity in Ohm-meters</u>
Wet Organic Soil	10
Moist Soil	100
Dry Soil	1000
Bed Rock	10000

In point of fact, the designer must design with a worst-case situation in mind. It is recommended that resistivity tests be performed under different weather extremes. Very dry conditions will cause the highest (worst-case) resistivities.

2.4 SUMMARY, GUIDELINES, AND RECOMMENDED PRACTICE

This final section of Chapter 2 presents 13 recommendations for designing effective ground systems. In so doing, it also summarizes the salient features of both above-ground and underground current paths which most efficiently and safely conduct the lightning into the earth. From this point of view, the above-ground paths are considered as an extended portion of the ground system.

1) The primary recommendation, which underlies all the recommendations, is to design the lightning protection system during conceptual planning of the wind turbine construction. Add-on protection is generally costly and less effective. If risk management techniques are employed, see Sections 2.2.2.1, 4.2, and 4.3.5 for necessary information.

The remaining 12 recommendations are presented in three categories: (a) recommendations 2 through 7 pertain to the extended ground system, beginning at the top of the tower; (b) recommendations 8 through 10 pertain to the ground (underground) system; and (c) recommendations 11 through 13 pertain to protecting personnel at the turbine site during thunderstorms.

2.4.1 The Extended (Above-Ground) Ground System

Beginning at the top of the tower:

2) Air terminals (lightning rods) atop the nacelle are advisable if vulnerable components (e.g. transducers) atop the nacelle need protection or if the nacelle is itself not a good conductor. The heights and spacing of the air terminals are determined by the location of the components. Many designers accept the cone of protection concept. A region of protection is formed by an imaginary cone with its apex at the top of the air terminal. The base radius of the cone is equal to or slightly greater than the height of the air terminal [4].

3) Damage to components inside the nacelle (e.g. generator, gearbox, electronics, etc.) may be ameliorated by a metallic nacelle acting as a shield. Further reductions in current flow through the most vulnerable nacelle components may be obtained by using methods enumerated below.

4) Damage to bearings and slip rings may be reduced or eliminated by providing alternate low-inductance shunt paths around them. The path may be a spark-gap skirt or metal straps with attached carbon brushes riding on a smooth surface to accommodate the relative motion between moving paths. Further reduction in the fraction of current flowing through bearings/slip rings may be attained by increasing the inductance of the path through the bearings/slip rings. This inductance may be increased by lengthening the effective path through which the current must flow.

5) Lightning-current-carrying down conductors should be designed to minimize their self-inductance or combined inductance if current is shared. In general, the shortest and straightest path between two points yields the minimum inductance. Also, the larger the size of the conductor the smaller will be its self-inductance. This means that a conducting tower of large radius will have less inductance than a thin conducting tower. Accordingly, the voltage drop along the tower will be smaller for the larger-radius tower. For a nonconducting tower a minimum of three down conductors spaced equally about the tower is recommended. Bends and corners in down conductors should be avoided because they increase inductance and the danger of sideflashes.

6) Guy wires, which are often employed with vertical-axis wind turbines, may be used to divert a portion of the lightning current to ground (see Section 2.2.2.1).

7) The size of both above-ground and underground "ground" conductors must be such that they can carry the worst-case fault currents from the power system, as well as, the lightning currents. Because of assumed longer time durations for fault currents, conductor size selections are generally dictated by fault current requirements. Thus, most "ground" conductors are #8 AWG or larger.

2.4.2 The Ground (underground) System

8) Connections within the ground system and at the entry point of the underground system are permanent or semipermanent. For permanent connections, welding is the preferred method of bonding. For semipermanent connections, bolts and clamps are preferred. When experienced welders are unavailable or where standard welding practices are difficult to follow, the exothermic Cadweld (TM) process has been employed.

9) The earth ground system should be designed to minimize the touch potential at the tower base, and its spatial bounds should extend radially beyond the point at which step potentials are lethal to humans and livestock. Such a ground system inherently will be a low-resistance system. Spacing of the connected buried rings or grids outside the footing/foundation of the tower base is a function of the earth conductivity and the worst-case lightning current expected. Consult references [1,9,15,23 through 36] at the end of this chapter for detailed design procedures. Also see Section 2.2.2.4.

10) Because the tower footing/foundation may extend outside of the tower base, the portion of the ground system designed to minimize touch potential must be incorporated inside the concrete. For such configurations it is convenient and desirable to utilize the reinforcing bars of the footing/foundation as part of the ground system. See Section 2.2.2.4.

2.4.3 Safety

11) It is recommended that personnel vacate the site during thunderstorms. For personnel unavoidably at the site during a thunderstorm, the safest location should be at the center of the tower at the base. Insulated flooring or mats increase safety. To lessen danger from touch potential, personnel should avoid touching all metal parts, cables and equipment.

12) Fences may be employed to exclude both humans and animals. However, when fences are employed certain dangers should be recognized [9]. If the fence is located at least six feet beyond the outermost extremity of the earth ground system and beyond the point at which step potentials are no longer dangerous, a fence can be an excellent safety feature. However, should a counterpoise extend beyond the fence a potentially hazardous condition is created where the fence and the ground near it may assume a dangerous potential difference. In very high human traffic areas it may be necessary to build an extensive earth grid system which extends at least five feet beyond the fence. In this case the fence must be solidly connected to the ground grid.

13) For high human traffic areas, it may be possible to obtain additional safety by depositing a layer (3 or more inches depth) of crushed rock on the earth's surface. See Sections 2.3.1.3 and 2.3.2.5. For walk-ways even better insulating mats may be advisable. It should be noted that the efficacy of crushed rock over a long period of time has been questioned. For such a layer to be effective, it must have a much higher resistivity than the soil it covers.

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Chapter 3

GENERATOR COMPONENT PROTECTION

3.1 INTRODUCTION

Placing a generator on top of a tower will increase the chance of lightning damage to the generator and its control components. Generating equipment normally used by utilities is located close to ground level. Its location within a shelter gives it protection not available to generating equipment located up to 100 meters above the terrain. Methods of protecting generating equipment are discussed in this chapter.

The characteristics and type of generating equipment on wind turbines varies with turbine rating. For small turbines, single phase and dc generators may be used. The generators for large turbines will normally be 60 hertz, 3-phase with line voltages from 480 volts to 4160 volts. Power ratings will vary from 100 kW to around 6000 kW for most existing and proposed commercial wind energy systems.

The drawing of a wind turbine in Figure 3.1 shows how some current could reach the generator if lightning strikes the blade. However, in order to reach the generator the lightning current would have to pass through the blade, hub bearings, low-speed shaft, gearbox, and high-speed shaft. Alternate paths also exist for this transient current so that only a portion reaches the generator.

A strike on the nacelle or tower could also induce voltages and currents in power cables and generator windings. Surges from lightning and switching on the power lines could also damage the generator. A summary of the sources of damage is shown in Figure 3.2. Figure 3.3 shows a view inside a typical wind turbine nacelle. The lightning protection designer should consider the merits of a nacelle fabricated of a conductor, or a nonconducting material. If a nacelle is made of a conducting material the threat to the generator and other tower components is greatly reduced. See Section 2.3.2.1.

The standard techniques for protecting generating equipment from lightning damage are documented in IEEE and ANSI standards [1,2]. A paper by Jackson [3] discusses surge protection of rotating machinery. Several general references [4,5,6,7] at the end of the chapter address surge protection of generators and other electrical equipment.

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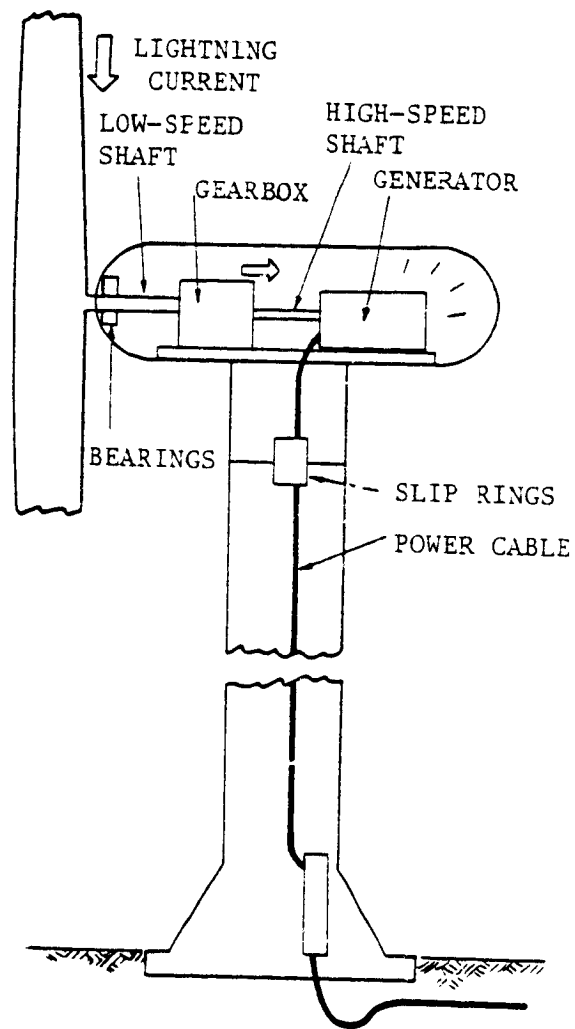


Figure 3.1: Possible Lightning Path to Generator.

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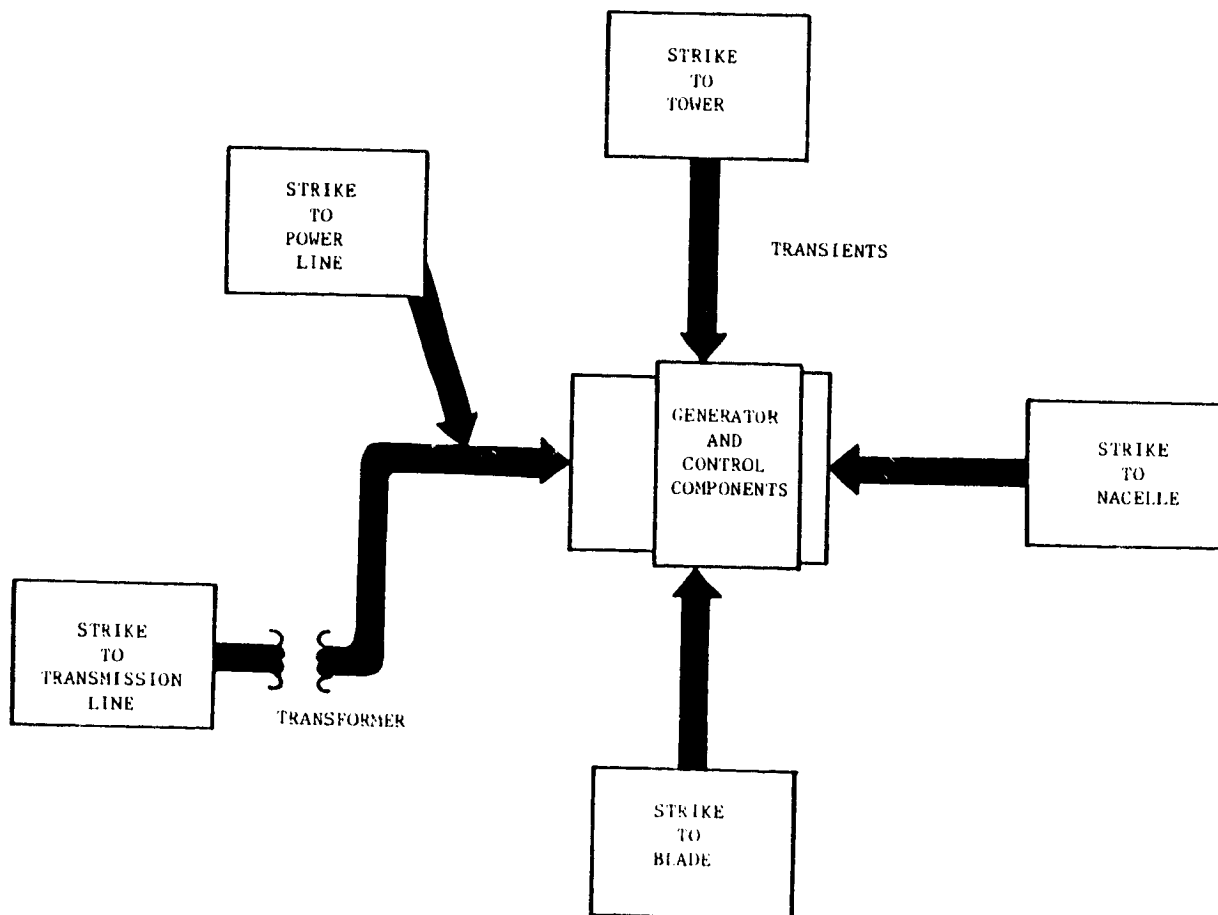


Figure 3.2: Sources of Lightning Caused Transients.

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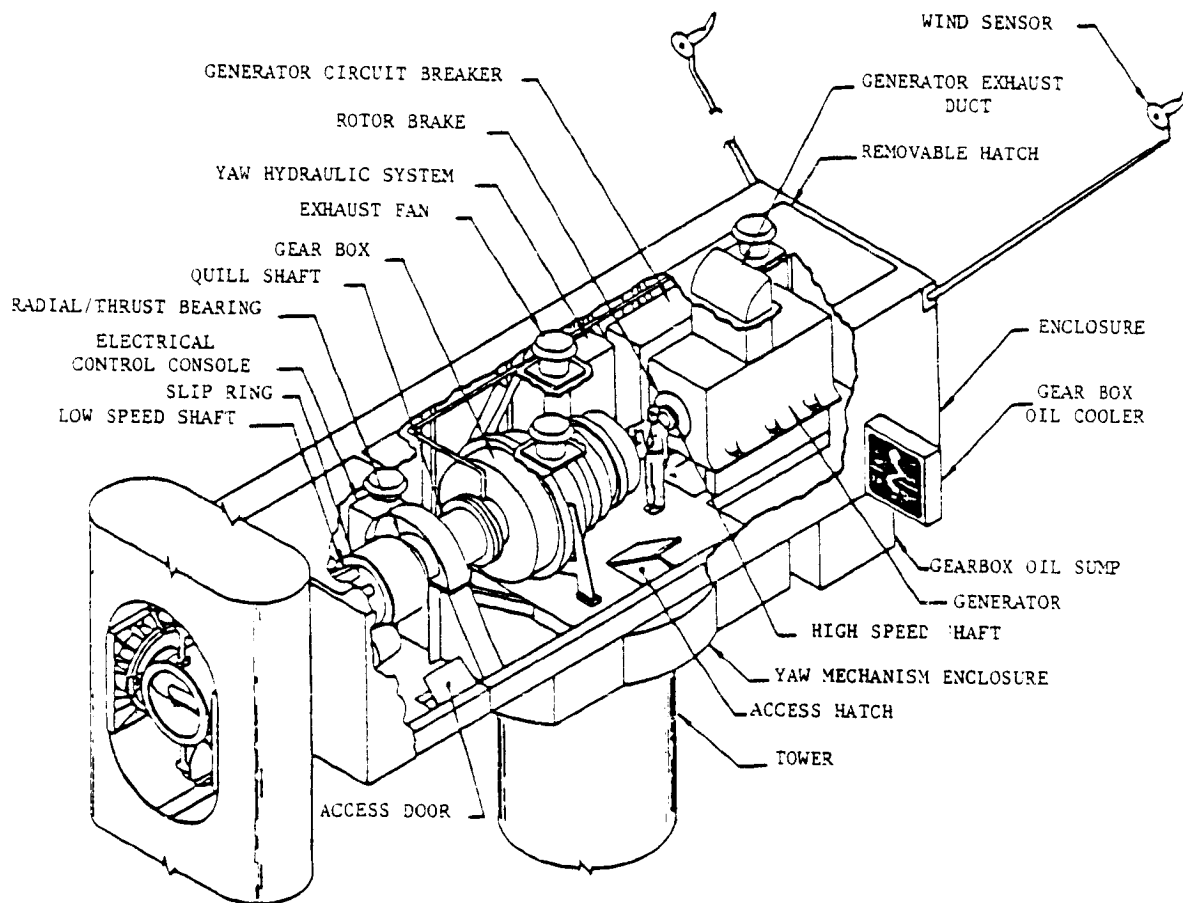


Figure 3.3: Rotor and Nacelle Arrangement.

3.2 GENERATOR AND CONTROL EQUIPMENT

Many different techniques can be used to transform the mechanical energy of the turbine into power line energy. Each design will have different electrical characteristics and components. The final result is a 3-phase 60 hertz voltage that goes to a step-up transformer connected to the power lines. The remainder of this section describes the most widely used energy conversion system.

A gearbox changes the low-speed, high-torque energy available from the turbine blade(s) to a speed suitable for an electrical generator. Whether a synchronous generator, induction generator, dc generator, or some other machine is used, the output speed of the gearbox is normally in the 1200 to 1800 rpm range. Although the induction generator is finding some acceptance, synchronous generators seem to be the most acceptable means for energy conversion. The methods for protecting a synchronous generator and its associated components are presented in this chapter. Protection of other types of generating systems will have some differences; however, the techniques for lightning protection for synchronous generators can be used as a guide for protecting other systems.

Synchronous generators require fairly complex excitation systems. A view of a typical excitation control system (Figure 3.4) indicates not only the field and stator windings need protection, but other electrical equipment may be subject to surge damage. The suppliers of the control equipment are aware of possible surge damage and normally build protection into their systems. Signal and power lines going into control equipment should have shields as described in Chapter 4. As with any lightning protection system, it is necessary to coordinate transformer, switchgear, control equipment, transmission lines, and generator protection equipment. The protection of transformers and transmission lines is normally provided by the utility company. The control equipment and contactors used for running the generator will normally be furnished by the wind turbine manufacturer. The turbine manufacturer should coordinate surge protection with generator and control equipment vendors and the utility company. Excitation systems should meet the minimum requirement of some accepted standard [8].

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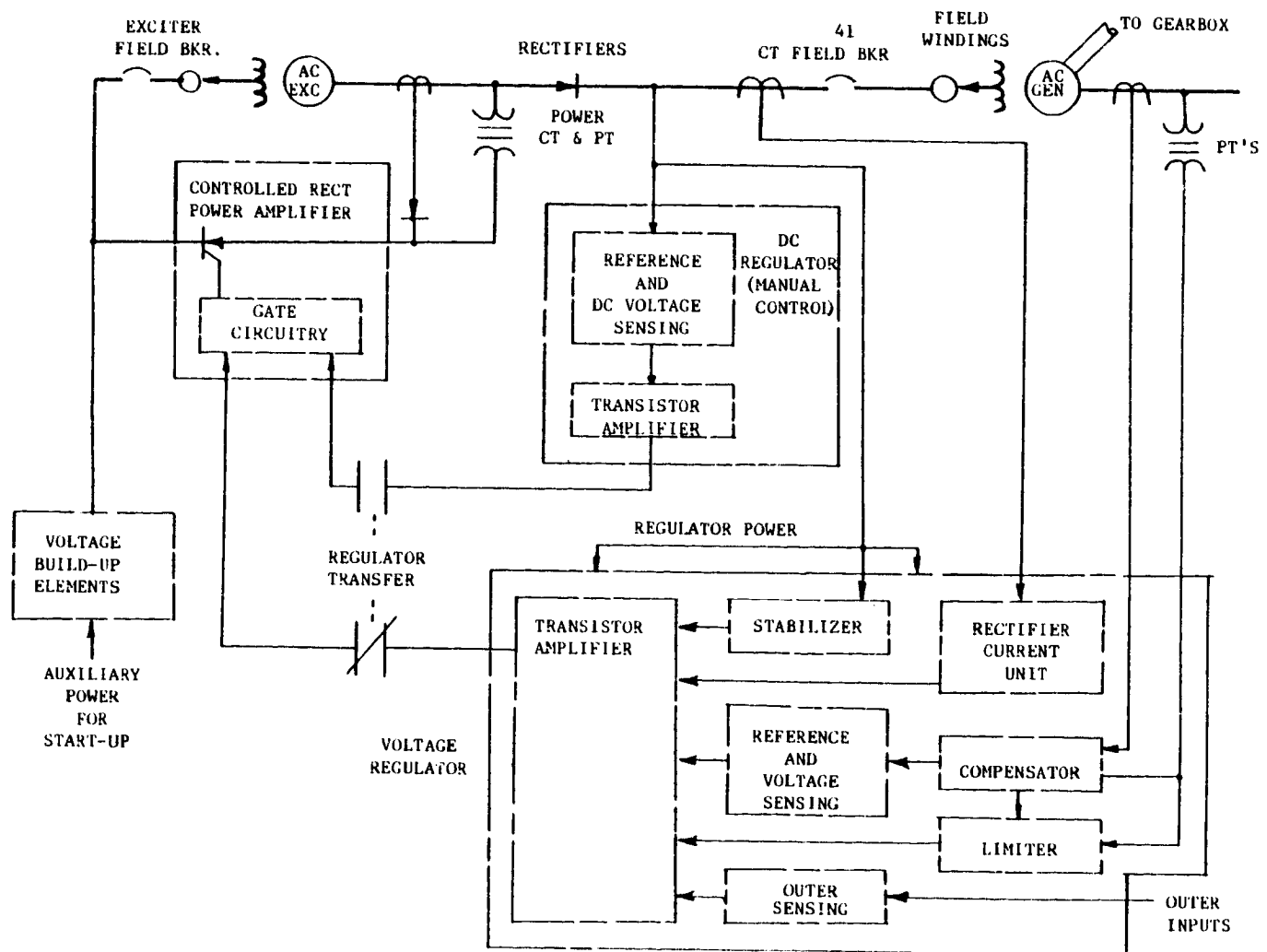


Figure 3.4: Typical Excitation Control System.

3.3 GENERATOR SHIELDING

Placing the generator in an enclosure that provides electrostatic and electromagnetic shielding, such as a metallic nacelle, would protect it from a direct lightning strike. Although there are some openings in a metallic nacelle for ventilation, shaft entrance and cables, the nacelle can be considered an equipment lightning shield.

The use of slip rings to pass some of the lightning currents from the turbine shaft to the nacelle will reduce the amount of current flowing to the inside of the nacelle. Electromagnetic shield screens placed in ventilator openings should cut down on energy entry in these apertures. Entrance of lightning from instrument cables can also be minimized with proper lightning protection. See Section 4.3.4. The levels of lightning currents and voltages inside the nacelle can best be determined by modelling and testing at a high-voltage laboratory.

Experience with a large number of in-field wind turbines will also help establish guidelines for protection of equipment inside the nacelle and several tower structures. Data must be collected and shared for the benefit of wind energy development.

3.4 DESIGN CONSIDERATION FOR ELECTRICAL MACHINES

It is possible that equipment contained in the nacelle could have potential differences that would cause arcing damage. If the frame of the generator were to reach a potential great enough to overcome the Basic Impulse Insulation Level (BIL) of the windings, puncture could occur which would require maintenance. The generator's insulation system must be maintained when a lightning transient occurs. Because of space limitations it is generally not possible to insulate generators to the same level as other electrical apparatus. There are two major problems to deal with in the surge protection of synchronous machines. First, insulation from winding to ground must be maintained. Second, the turn insulation must be protected. The effect of a steep voltage waveform on windings is shown in Figure 3.5 [4]. Reduction of voltage levels between windings can be obtained using the techniques in Section 3.5.

Surge protection techniques for protecting rotating machinery have been very successful [3]. It is very unusual for a machine to be damaged if recommended procedures are used. Although placing arresters and surge capacitors in the nacelle will cause this small area to become more crowded, they do give an added measure of protection. In some cases, lack of space in the nacelle may force design changes for the protection system.

A point made by Jackson [3] seems to indicate that to some extent overprotection may cause down time. His argument that reliability can be reduced by adding unnecessary equipment is certainly valid. If the nacelle provides adequate shielding and surges entering from the power lines are

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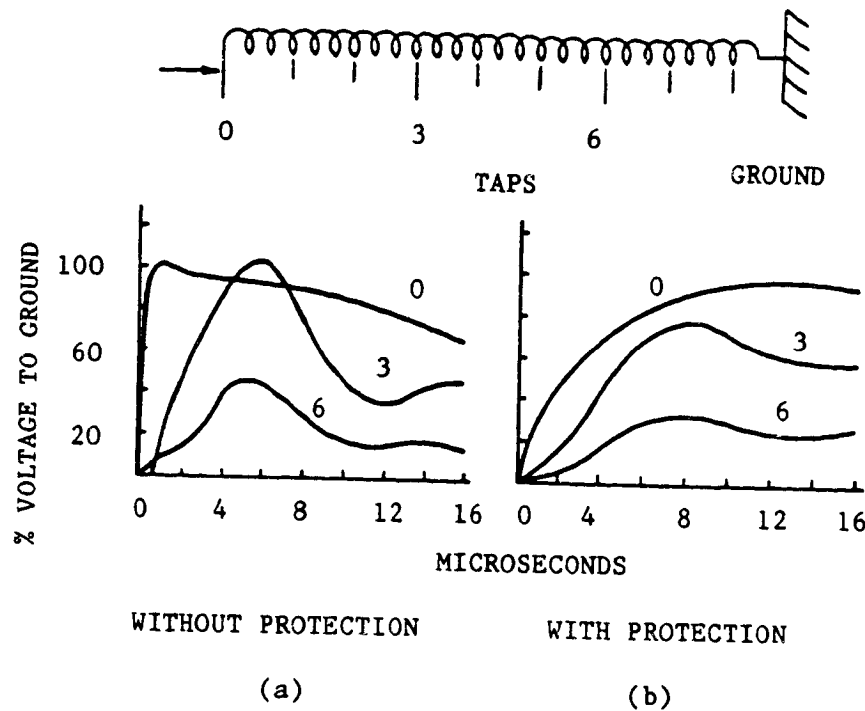


Figure 3.5: Distribution of Surge Voltages in Generator Winding.

sufficiently dissipated by the transformer protection, then generator surge protection equipment is unnecessary. It should also be added that the temporary overvoltages (TOV's) at the generator due to responses in the wind turbine control system could cause stress on the arresters.

The security of the generator insulation system is complicated by the fact that cumulative damage occurs to insulating materials. No simple techniques are available [9] which can integrate the cumulative effects of sequentially applied overvoltages. For example, an item may pass a high-voltage test for 50 seconds and fail if it is extended for an additional 10 seconds. This means that lightning could have a cumulative effect on generator insulation materials.

The design example in the next section introduces designers to an accepted surge protection technique for generators. The added protection of arresters at the generator is a good investment. At this point in wind turbine development it is the manufacturer's and perhaps user's decision to determine if their generator needs this added protection.

3.5 A DESIGN EXAMPLE

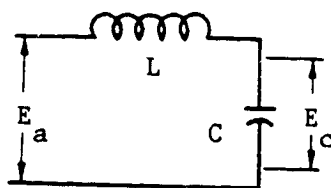
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The example that follows illustrates how to protect the generator by limiting the voltage stresses from conductor to machine iron ground and between turns of the windings. The generator is treated as a transmission line with distributed constants. The voltage along the conductor produces a voltage between turns. The lower the rate of rise of this voltage, the lower the stress between turns. The rate of rise can be controlled with a circuit, as shown in Figure 3.6(a), which consists of an inductance and capacitance in series [3]. If a constant voltage E_a is impressed on the series circuit, the voltage E_c across the capacitor will be oscillatory until the circuit losses dampen out the oscillations. The voltage, E_c , oscillates about E_a with a period,

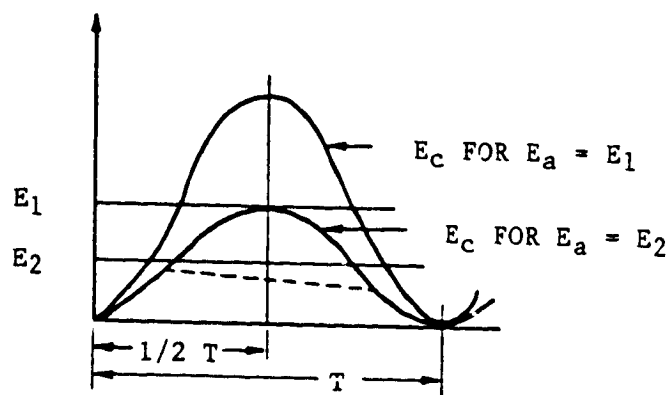
$$T = 2\pi(LC)^{1/2}$$

and the time to reach its peak is $T/2$.

By properly choosing the values of L and C , the time to peak can be kept to a minimum. The value of E_a also has an effect on determining the rate of rise as shown in Figure 3.6(b).



(a)



(b)

Figure 3.6: Inductance and Capacitance in Series.

Therefore three elements are required to limit the rate of rise of voltage between turns: an inductance, a capacitance, and a way to limit E_a . E_a is limited, in practice, by a lightning arrester at the line terminals of the distribution transformer. The generator is connected in parallel with the capacitor so the surge impressed from generator terminal to machine iron ground is E_c . This system alone will not protect the generator because, as shown by Figure 3.6(b), E_c could exceed E_a , which endangers the insulation from conductor to iron. To insure good protection E_c should be kept equal to or less than E_a . This can be done by installing another arrester in parallel with the capacitor. When E_c rises to the sparkover voltage of the second arrester, it limits E_c as shown by the dashed line in Figure 3.6.

A typical circuit of a lightning protection system for a generator is shown in Figure 3.7. The in-line inductance, L , may be an inductor or the distributed inductance of a length of line. The capacitor, C , is of special construction for surge protection. The arrester for the line is either an intermediate or distribution type. A special arrester for rotating machines should be specified for the generator.

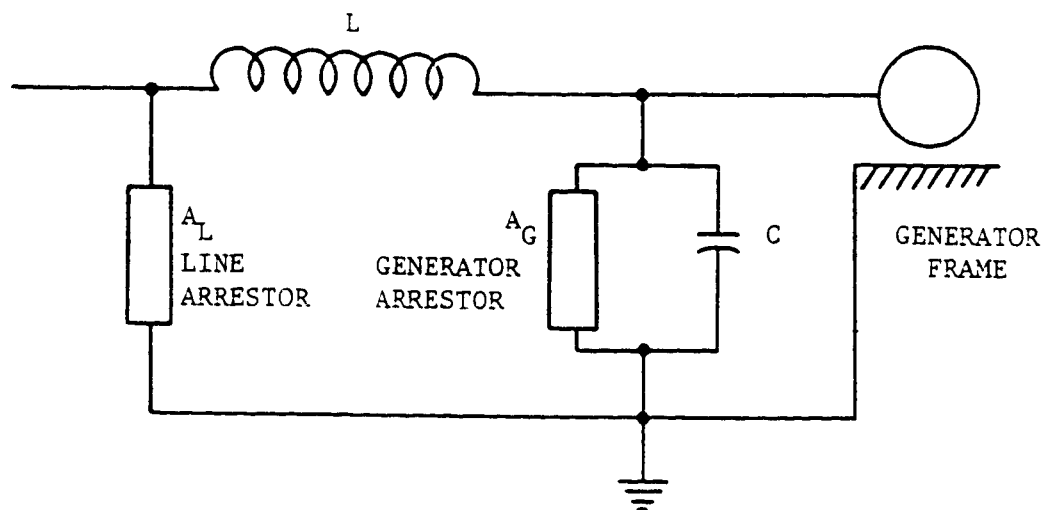


Figure 3.7: Fundamental Protective System.

The purpose of an arrester is to limit the peak voltage. In order to accomplish this task it must act as an insulator during normal 60 hertz voltage generation. It must act as a conductor to high currents from a lightning surge. After the lightning current becomes negligible, it must again act as an insulator to the normal generator voltage.

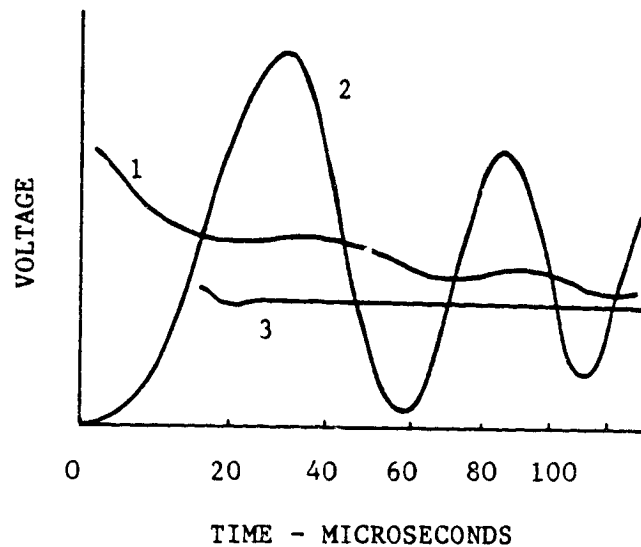
Selecting the arresters, inductance, and capacitance is illustrated in the example contained in the next few paragraphs. The data that have been included in the example will be useful in designing protection for most generators used on wind turbines.

A generator with a rating of 4160 volts would be a probable candidate for a large wind turbine. Its power rating and size will depend on the overall design of the wind energy system.

For a 4160 volt generator a standard 0.5 microfarad surge capacitor is selected [4,9]. The inductance, L , may be a lumped value [4] or a length of transmission line not less than 1500 feet [3]. If the machine's BIL is 12.73 kV, then an arrester which sparks over at a lower level must be selected. For the arrester, A_G , a 3 kV special arrester for rotating machine with a breakdown voltage of 12 kV [4] is selected. This provides a protection margin of 730 volts.

The line arrester, A_L , not only protects the transformer, but is part of the generator protection system. Its rating will depend on the insulation characteristics of the transformer. It may be an arrester that has sparkover a little higher than the generator's arrester.

Figure 3.8 [3] illustrates a cathode-ray oscillogram of voltages taken from laboratory tests which show the voltage across the line arrester, and the voltage across C with and without the machine arrester, A_G .



CATHODE - RAY OSCILLOGRAMS OF VOLTAGE IN THE
PROTECTIVE SYSTEM [4]:

- 1) VOLTAGE ACROSS A_L ;
- 2) VOLTAGE E_C , ACROSS C WITH A_G NOT CONNECTED;
- 3) VOLTAGE E_C , WITH A_G CONNECTED.

Figure 3.8: Surge Voltages on Generator Line.

3.6 CONCLUSIONS AND RECOMMENDATIONS

The generating equipment of a wind turbine needs some level of lightning protection. Surge damage has occurred to rotating electrical machinery in less severe lightning environments. A wind turbine generator can be damaged not only from power line strikes, but also from strikes to the blades, the tower, or the nacella. Because of space limitations the insulation on rotating machine windings is held to a minimum. Hence generators are more susceptible to surge damage than other electrical power equipment.

Several factors must be considered when evaluating the protection of generating equipment. The chances of a lightning strike are related to the number of thunderstorm days per year and the local topology. As wind turbine arrays develop the chances of lightning entering the electrical systems will increase. If the power grid connected to the wind turbine has surge protection, the wind turbine generating system will be less susceptible to lightning damage.

Not only are the windings of electrical machines subject to lightning hazards, but the generator's controls and monitoring equipment may be damaged. Bearings pitted by arcing will fail prematurely. Diodes on a brushless

synchronous generator may need replacement after a lightning strike. The electronic controls of a generator must also be protected.

Since turbines have a variety of structures and are fabricated of several materials, the amount of electromagnetic shielding differs with each machine. Because of these factors it would be inappropriate to make recommendations that cover all generating systems. However, the following guidelines will be of value when designing generator protection:

- o Discuss with the manufacturer the possibility of modifying the basic impulse insulation levels of the generator.
- o Specify that the electronic control equipment has shielding and surge protection.
- o Provide a shield, such as a metallic nacelle, which encloses the generating equipment.
- o Coordinate generator and power line surge protection design.
- o Provide protection to special monitoring equipment as discussed in Chapter 4.
- o Provide a by-pass path for lightning current resulting from a blade strike.

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Chapter 4

ELECTRONIC SUBSYSTEM PROTECTION

Transients caused by lightning may damage the electronics subsystems and/or cause false data. General lightning characteristics are discussed in Chapter 2. In this chapter we discuss protecting electronics subsystems by

- o describing the characteristics of lightning transients and the means by which lightning transients gain access to electronics,
- o presenting the fundamentals of protecting electronics from lightning transients, and
- o recommending practices for reducing the effects of lightning transients.

4.1 LIGHTNING TRANSIENTS

This section discusses two topics: characteristics of lightning transients and the means by which lightning transients may gain access to electronic equipment.

4.1.1 Characteristics

Lightning is the rapid flow of large amounts of electrical charge. Fringe effects related to electric charge flow such as weak electric and magnetic coupling and electromagnetic radiation usually can be ignored. However, in the vicinity of any lightning stroke they become significant phenomena for electronic subsystems. A wind turbine designer must pay close attention to these effects if electronic problems caused by lightning are to be averted.

4.1.1.1 Magnitude and Physical Distribution

A lightning stroke may have a peak current from a common 20,000 amperes to a very rare several hundred thousand amperes [1]. Potential differences along a stroke path usually average about 900,000 volts per meter [1]. This

causes widespread transients of lesser magnitude to flow and radiate for a considerable distance away from a main stroke. Solid state devices can be damaged by lightning transients as shown in Table 4.1 [2].

TABLE 4.1

Typical Breakdown Voltages for Semiconductors

Device Type	Electrostatic Discharge Susceptibility (volts)
MOSFET	10-200
JFET	140-10,000
CMOS	250-2,000
SCHOTTKY DIODES, TTL	300-2500
BI-POLAR TRANSISTORS	300-7,000

A wind turbine tower may be viewed as a transmission line with an open circuit discontinuity at the tower top and a short circuit discontinuity at the tower bottom. Such characteristics of a tower would cause an in-phase voltage reflection of the lightning transient from the top of the tower and an in-phase current reflection from the bottom of the tower. If the tower is viewed briefly as a pure inductance of about 2 microhenries per meter, a lightning stroke leading edge rising from 0 to 200,000 amperes in one microsecond would give, $E = L di/dt = 400,000$ volts per meter. The transmission line discontinuity could then give a worst-case voltage doubling as high as 800,000 volts per meter at the top of a tower and current doubling as high as 400,000 amperes could occur at the tower bottom. This analysis thus gives values that a designer can use to make a wind turbine system less susceptible to lightning.

For a 99+% confidence level, a designer can use the above as maximum values of voltage gradient and stroke current for the lightning transient if the tower is struck directly. Since the top and bottom of the wind turbine tower are not perfect open or short circuits, neither perfect wave doubling or wave cancelling occurs. A maximum of 200,000 amperes at the tower top and 400,000 volts per meter at the tower bottom is assumed for a 99+% confidence that actual stroke currents and voltage gradient values would always be less than those used for the design.

By way of comparison, dry air at standard pressure (30 in. Hg.) and temperature (20 degrees C) ionizes at about 3,000,000 volts per meter [3]. At

this voltage gradient, ionized air will carry a lightning stroke along the path. Such a high gradient can be obtained locally on sharp points as a peak voltage gradient even when the tower voltage gradient is much lower.

Since the peak current and voltage gradient magnitudes in virtually all lightning strokes are so large, damaging transients flow and radiate across and through the entire region in all directions from a main stroke for a considerable distance. It is necessary to consider the stroke as a three-dimensional, volume-filling phenomena. Potential differences of sufficient magnitude to damage electronics may exist between points in space separated by small distances in any direction in the vicinity of a wind turbine subjected to a direct or nearby lightning strike.

4.1.2 Time and Frequency Domains

The lightning transient may contain from one to thirty-four pulses [4]. Each pulse will usually have a steep leading edge and a long trailing tail. The leading edge may have a rise time from about forty nanoseconds to a few microseconds [5]. The steep leading edges of the pulses give rise to a very wide radiated energy spectrum. The long tail usually lasts over a hundred milliseconds. It is this portion of the pulse in which the bulk of the energy of the lightning transient flows. Although such a large electrical transient as a lightning stroke has much electronics damaging energy in the fast rising leading edge of the pulse, the long trailing tail is the part of the stroke containing most of the energy. Capacitive shunting, inductive isolation, and reflective intervening surfaces tend to reduce the high frequency content of a lightning transient as it travels away from the main discharge. Except for directly encountered lightning fields (without much intervening reflective material or inductive circuit path), a rise time of between 1 and 2 microseconds and an exponentially decaying tail of about 150 milliseconds are typical, with about 3 or 4 such strokes per lightning flash. The radiated frequency spectrums of lightning, on average, peaks between 5 and 10 khz and then decreases as $1/f$ as shown in Figure 4.1 [6]. The spectrum of conducted lightning return strokes tends to be flat below several khz, and then fall off inversely with the frequency squared above several tens of khz [6].

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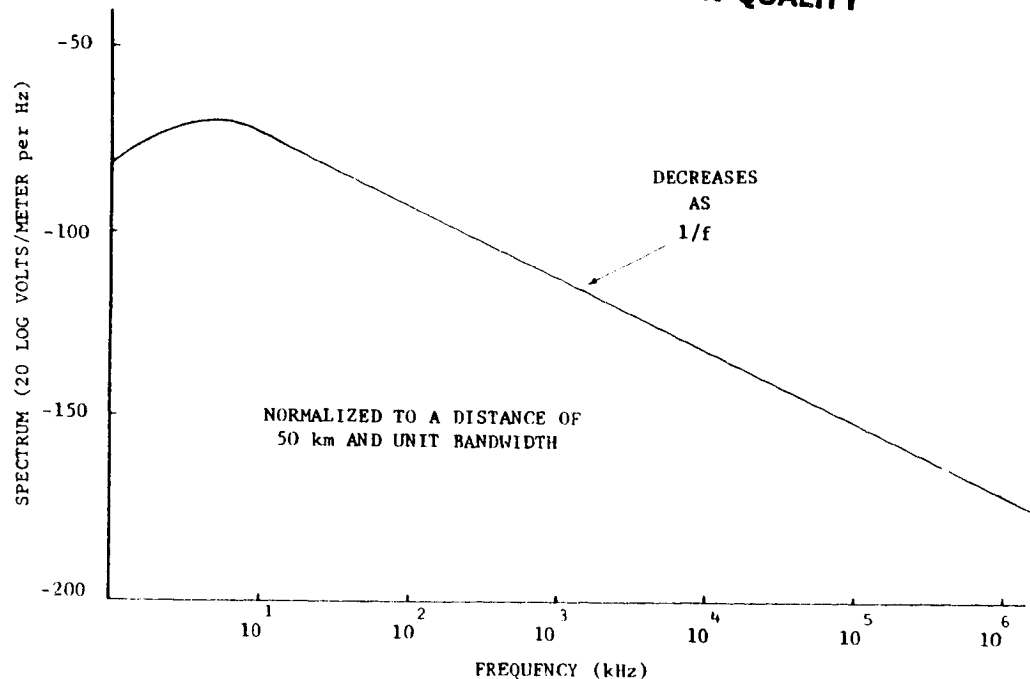


Figure 4.1: Composite Radiated Spectrum of Lightning [6].

4.1.2 Entry to Electronics

Lightning transient energy may gain access to electronic equipment by means of conduction and electromagnetic field coupling.

4.1.2.1 Conduction

Transient energy is conducted to the electronics by such paths as outside power lines, telephone lines, and local sensor and control wires. While nearby strikes are of concern, a direct wind turbine strike is the most serious case. The lightning produced voltage gradient acts as a transient source to spread significant energy in all directions for a considerable distance. The flow will be in all directions around the electronics, not just between cable pairs. For example the path may be along external cable shields, from the electronics input to the output, or along the electronic subsystem housing. The total voltage around any closed loop must sum to zero. This means a voltage applied to one portion of a closed loop forces a corresponding opposite voltage elsewhere in the closed loop. So if

substantial transient current is conducted along any portion of a voltage loop (see Figure 4.2), loop potentials can be altered so that the voltage across electronic components may reach unacceptable levels.

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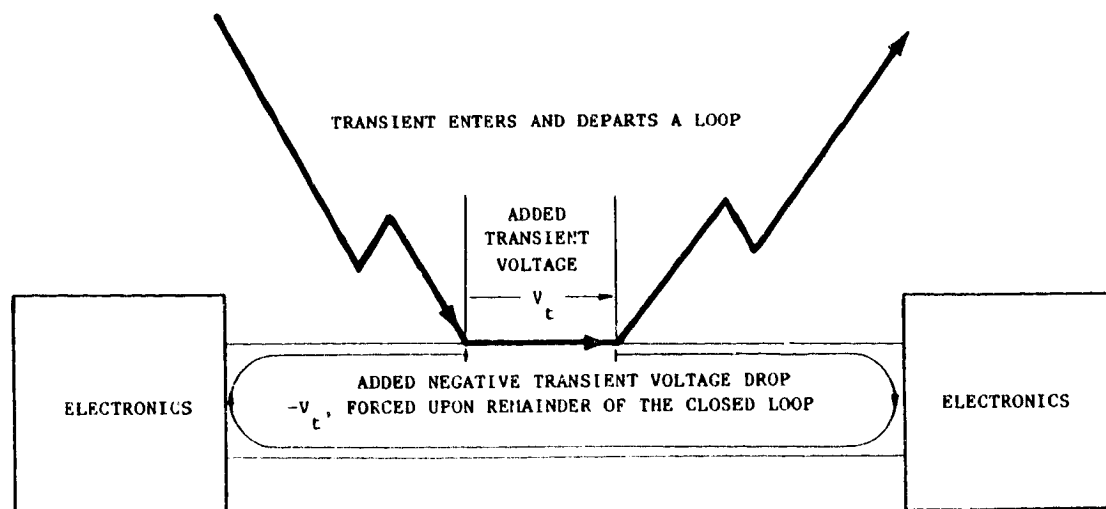


Figure 4.2: Transient Added to Sum of Voltages Around A Closed Loop.

This small piece of the lightning path in common with the electronics loop may be the common grounding network between electronic circuits, or from one side of the tower structure to another point on the tower structure with closely mounted electronics wiring. Lightning may convert some regions of dielectric into ionized conductors, and thus modify the original wind turbine circuit topology.

4.1.2.2 Electric Field Coupling

If the 800,000 volts per meter from Section 4.1.1.1 is considered on a per centimeter basis, the electric field would be 8,000 volts per centimeter. Many integrated circuits and other electronic components will fit into a space less than a cm. in height, but still will not stand a potential gradient of 8,000 volts per centimeter. Other orientations of the component or leads to the component could make the potential across the component even higher. Any two conductors separated by a dielectric have some capacitance between them. If a low-impedance path is established to one side of the capacitor (see

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Figure 4.3) from a particular potential and also to the other side of the capacitor from another potential, then the voltage gradient across the capacitor dielectric can be larger than the average voltage gradient in the region. This can lead to capacitor dielectric breakdown.

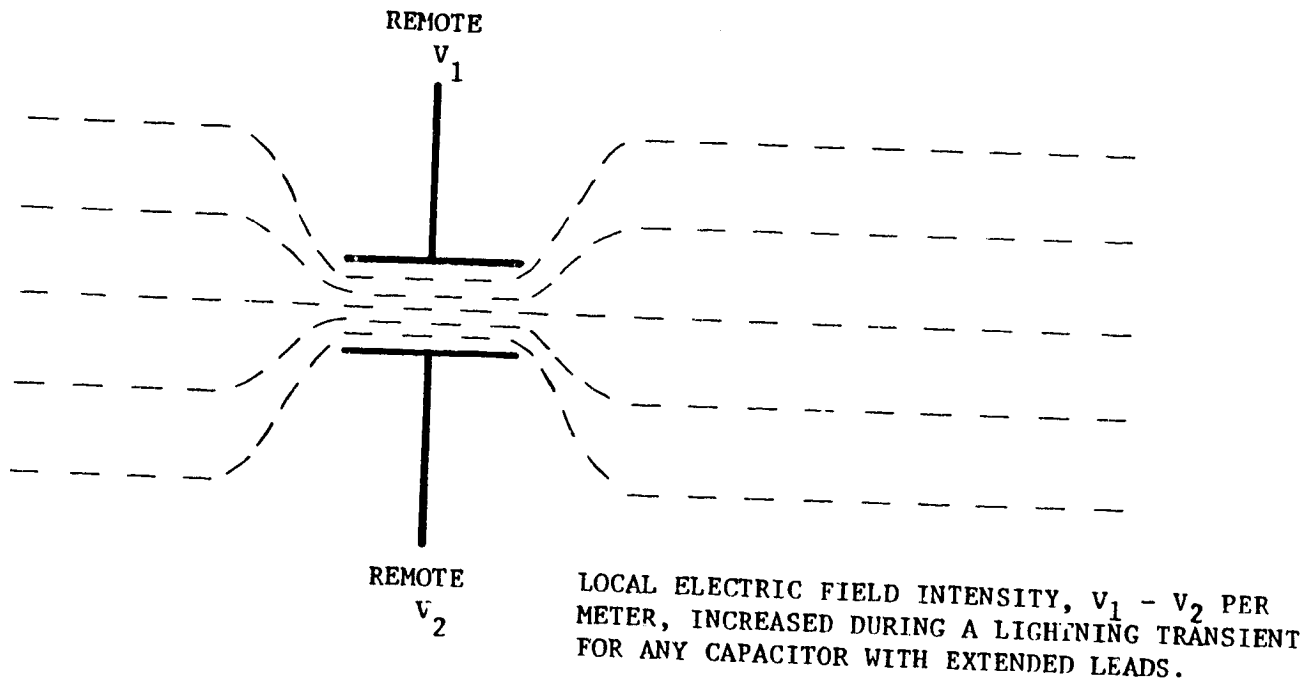


Figure 4.3: Low Impedance Access of Transient Voltages to Capacitive Situations.

If one side of the capacitor is effectively near ground potential while the other side is at the potential existing many meters up the tower with an average of 800,000 volts/meter along the tower, dielectric breakdown is essentially certain. For example, the shield of a co-axial cable could be tied to a ground wire which is connected to a rod buried in the ground while the center conductor is attached to a sensor at the top of the wind turbine tower. The shield may not be connected at the top of the structure to avoid ground loop currents flowing through the shield. But a lightning strike at the top of the wind turbine will break through the cable sheath to flow down the shield to the ground below. On the way a significant amount of energy may enter the connected electronics as well. How to deal with these problems will be covered in Sections 4.2 and 4.3.

4.1.2.3 Magnetic Field Coupling

All lightning transient current flow is accompanied by magnetic flux linkages between the current flow and with any wires in the vicinity. Changing flux linkages induce voltages across conductors. So as the transient current rises in magnitude, the flux linkages increase inducing a voltage in these wires. The most voltage is induced in wires that are parallel to the direction of the current flow. No voltage is induced in wires by a transient current flow perpendicular to the wires. Voltages can be induced into portions of a voltage loop or the total loop. For example, rather than a direct current flow through a portion of a loop, as shown in Figure 4.2, the added voltage V_t , could be caused by changing flux linkages from a nearby lightning transient current flow. Since the changing magnetic flux links both conductors of a pair it is the difference in flux change experienced by each wire which results in a net current flow in a loop. For example, wires separated by 1 cm. which run parallel to a stroke path one meter away in which current rises from 0 to 400,000 amperes in one microsecond, will have a loop transient potential induced per centimeter of length as shown in Figure 4.4 [7]. Notice that two conductors, say traces on a printed circuit board which are parallel to a tower structure located a meter away, would receive about 8 volts per centimeter of wire pair length. These values represent the maximum amounts that should be expected at the bottom of a wind turbine tower, per centimeter of length.

A strike near a wind turbine tower, but not actually contacting the structure, will induce electric and magnetic fields into the electronics as discussed above. The distances between the strike and the electronic components will be such that the induced voltages that are received will only be significant if long metallic wires are connected to the components, such as those that may be used to run to sensors or controls. The power and telephone lines have significant lengths, but pick up little radiated energy since they run in a direction which generally is perpendicular to the stroke path. The energy radiated from a rapidly rising leading edge of a nearby lightning strike could reach damaging levels for a poorly protected system. All wires can be considered as antennas. The gain patterns for various orientations and lengths of wires will affect the amount of transient induced. This can get very complicated. However, if direct turbine lightning strike and externally conducted lightning transient entry are protected against, then virtually all other sources of lightning electromagnetic energy will have also been protected against.

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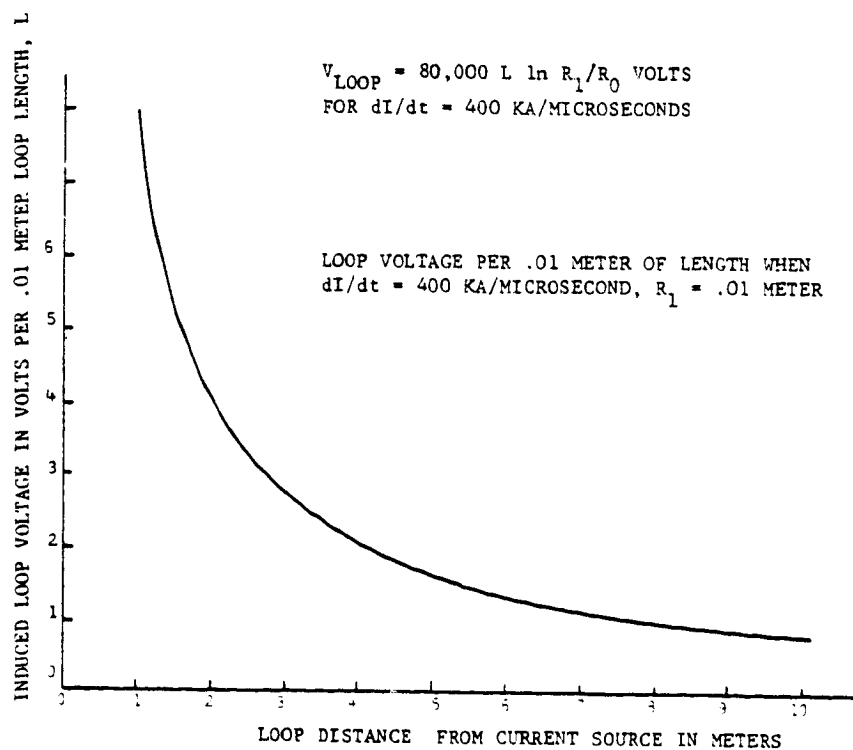
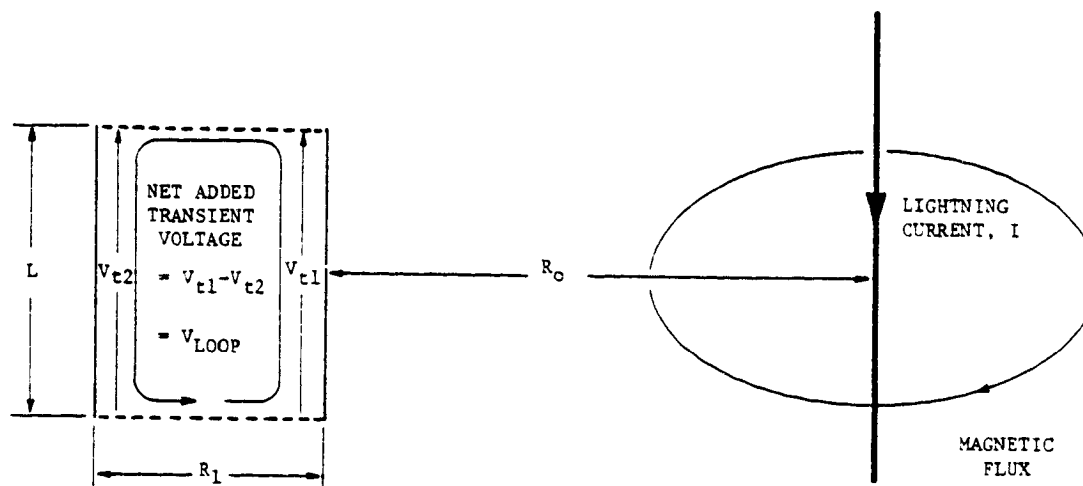


Figure 4.4: Net Added Transient Voltage
Induced in a Parallel Conductor Loop
by a Lightning Transient Current.

4.2 ELECTRONIC PROTECTION FUNDAMENTALS

The three fundamental concepts to consider in protecting electronics from lightning transients are:

- o the basic underlying philosophy,
- o the protection techniques, and
- o maintenance of data integrity.

4.2.1 Protection of Electronics Philosophy

Electronics play a key role in many wind turbine systems to provide critical safety and control functions. The electronic decision making circuitry of the system operates on information from sensors which detect such parameters as wind direction and intensity, blade icing, generator and power line phasing, etc. This data is necessary to coordinate wind turbine power generation with power system needs and operation, as well as to shut down the wind turbine when unsafe conditions occur. This latter function of the electronics requires special attention to prevent spurious wind turbine actions caused by misinformation (and thus erroneous decisions) when the system is subjected to lightning strikes. Electronic circuits need not be destroyed immediately by lightning for a wind turbine system to have problems caused by lightning. Not only must electronic circuitry be protected from direct destruction, but also from behavioral aberrations. Weakening of circuit components by repeated electrical overstress, as well as temporary false values in data circuits (called upset in digital terminology), can be dangerous. Upset can be caused in digital circuits by an extra volt added at the wrong instant. In an analog circuit reactive elements may be forced to erroneous values and cause a dangerous transient signal. All levels of voltage from minor noise due to distant lightning radiations to direct strikes to the wind turbine tower are encountered. Direct strikes are clearly dangerous, while lesser transients can have insidious effects if not anticipated in the planning of the wind turbine system. Figure 4.5 summarizes the different types of lightning strike damage from which wind turbine electronics must be protected.

4.2.1.1 Multilayered and Multileveled Protection

Multilayer protection (see Figure 4.6) refers to having environmental regions which are increasingly more benign because transient reduction has been provided in each layer. It is possible to have an outer shielding and transient suppression layer which disposes of the main part of the strike energy. The protection devices in this layer may react a bit slower than the initial rise of a transient, but can withstand the brunt of the energy from a

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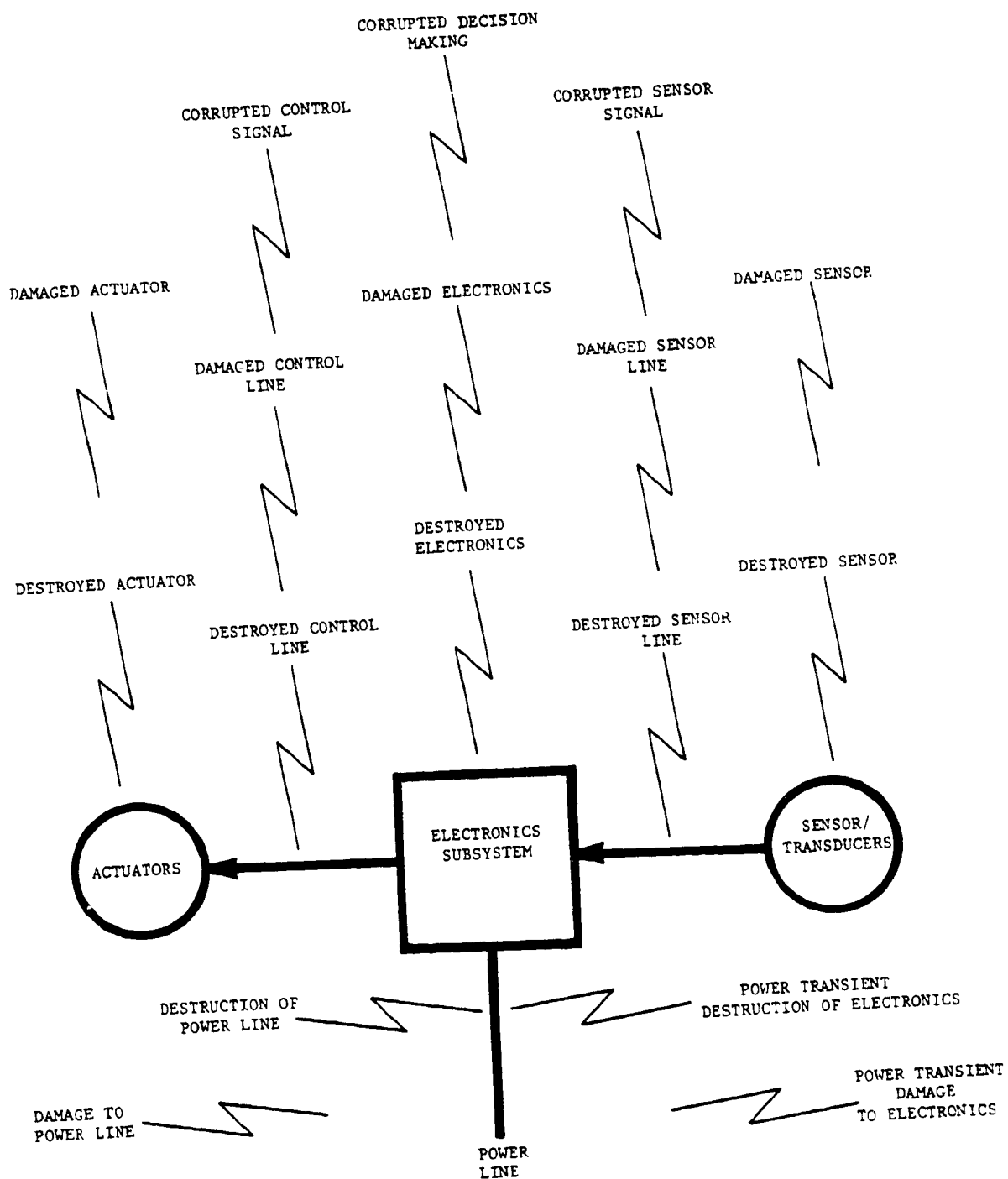


Figure 4.5: Types of Lightning Damage to Electronics Operation.

lightning strike. Within this outer layer is a region where a smaller residual transient environment is encountered. Another layer of shielding with lighter duty and faster transient suppression devices reduces the size of transients passing through this layer of transient protection. This process is carried on until an acceptable transient environment is obtained inside the innermost layer of transient protection.

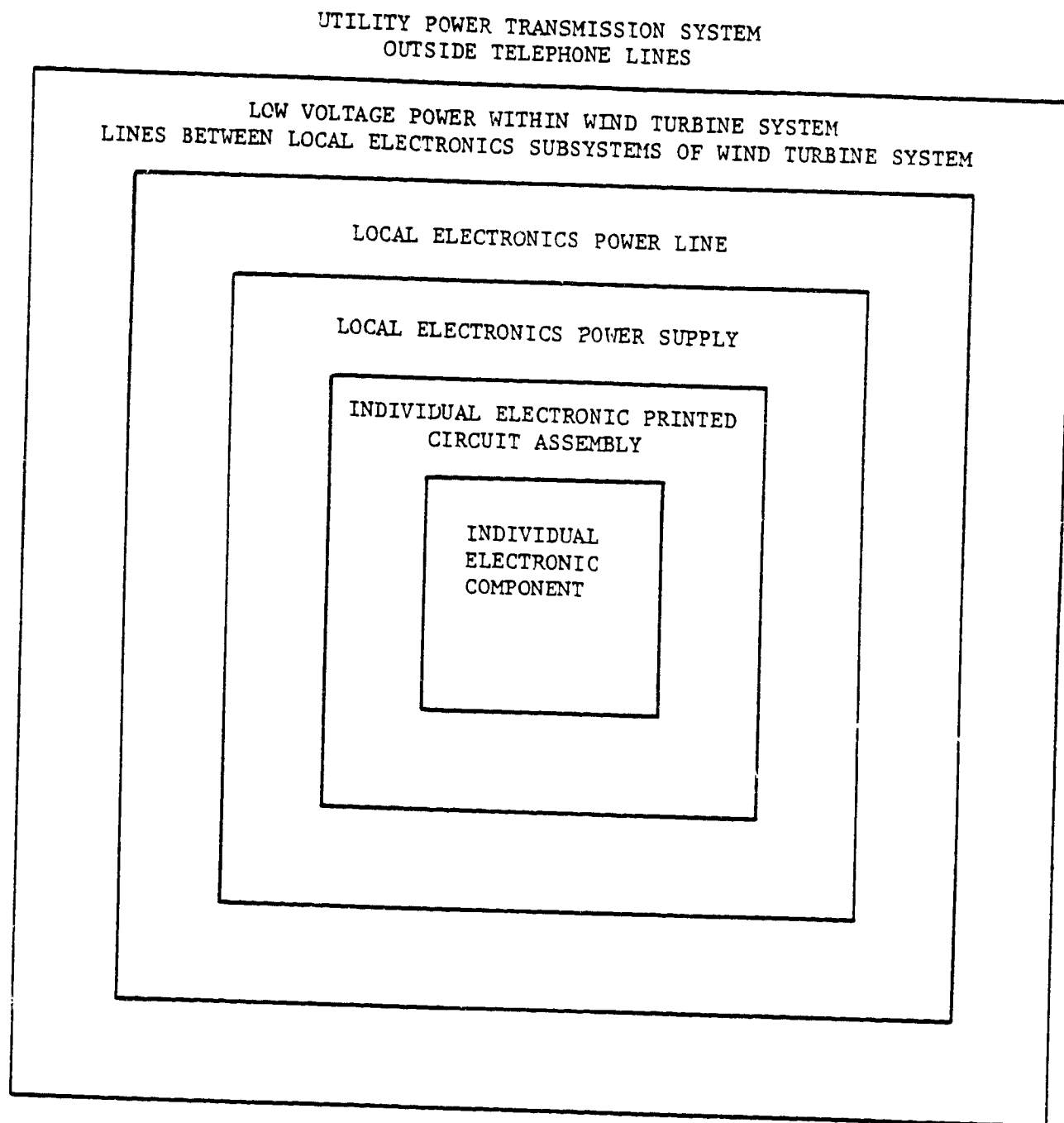


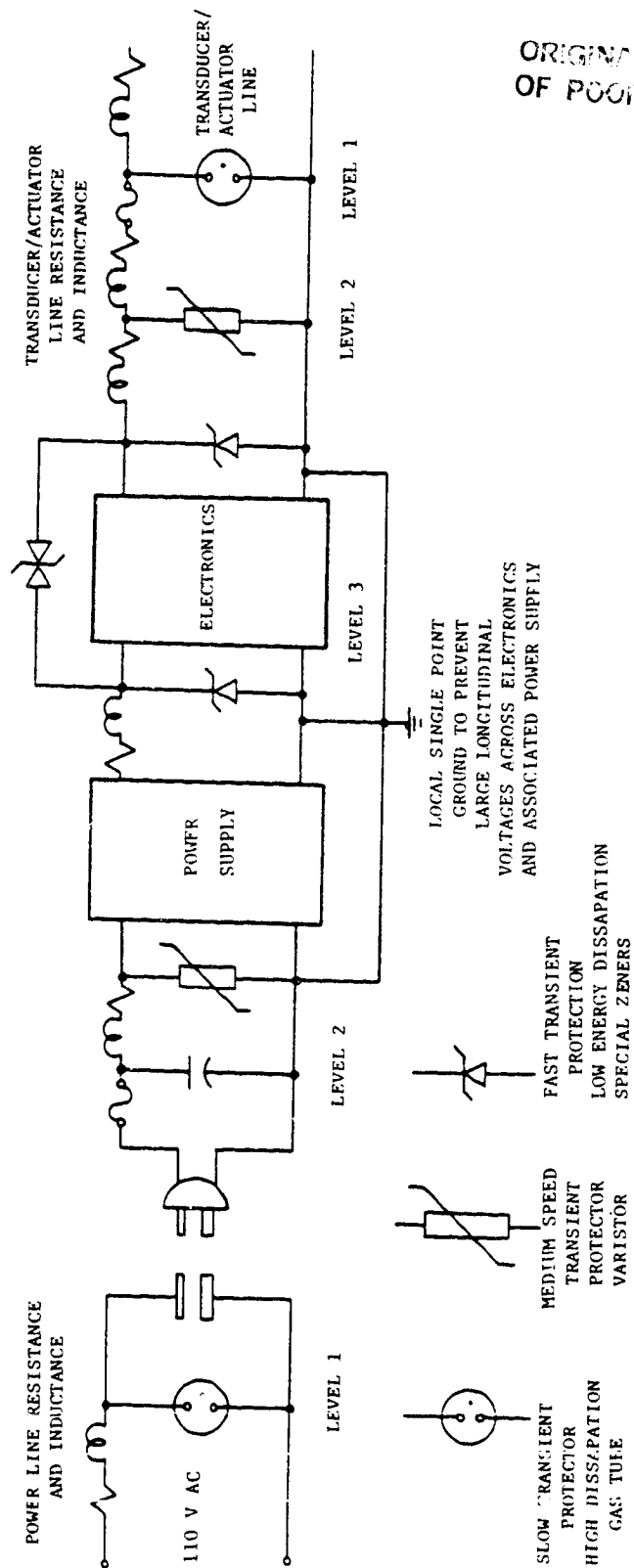
Figure 4.6: Multilayered View of the Electronic Environment.

Multilevel protection (see Figure 4.7) refers to the different energy and/or voltage levels at which transient suppression devices operate. Utility lines have very large fuses and surge arresters which drain off powerful direct strike lightning energy, passing on a reduced transient level to the local service lines. At the local service level, lighter duty devices at lower voltage levels further reduce the transient level, etc. until at the component level, transients have been reduced to an energy/voltage level that can be tolerated without component deterioration. At each stage, the transient must be reduced to energy/voltage levels that operating components can tolerate without degradation.

Layers may include physical shields, usually taking more than one layer to reduce all forms of transient entry to acceptable levels. Because levels of operation of transient devices differ, several levels of protection are usually needed to provide transient protection.

4.2.1.2 Multipath

Since a lightning discharge disperses energy in all directions, electronic devices must be protected not only across input/output pairs, but also between the input and the output of the devices. Not only must cables protect data from loss due to normal operating environmental noise, but they must not be destroyed by the occasional lightning strike. Lateral and longitudinal protection is required. In Figure 4.8, devices 1 and 2 provide lateral protection, while device 3 provides longitudinal protection.



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Figure 4.7: Multilevel Approach to Transient Magnitude Reduction.

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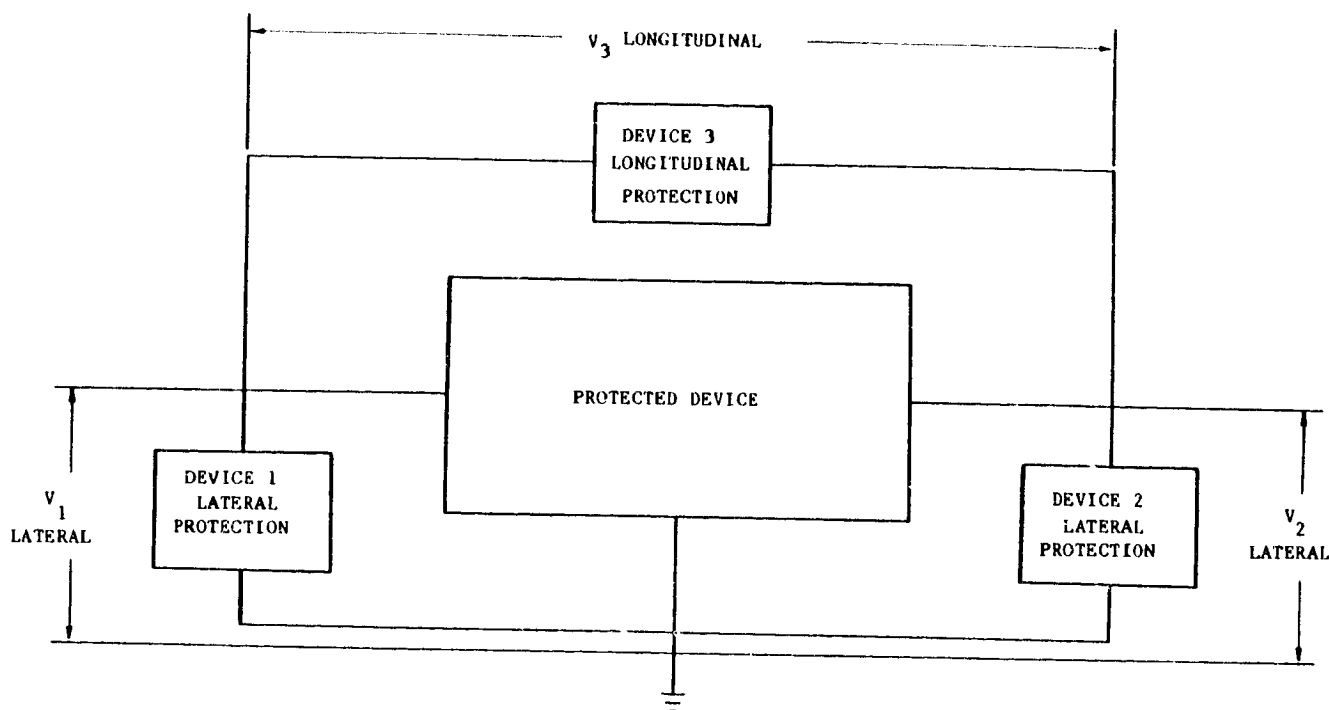


Figure 4.8: Multipath Protection of Electronics.

4.2.2 Electronic Protection Techniques

Two basic techniques, used for electronic subsystem protection, are transient shunting past the subsystem and subsystem isolation from the transient. In addition, during lightning transient disruption of the electronics subsystem operation, it is often necessary to retain vital electronic data until normal subsystem operation and communication on the data links can be restored. Interruptions may be only for a few microseconds, or milliseconds, or the time required to replace components.

4.2.2.1 Shunting for Protection

Shunting protection is obtained in two basic ways. One is by directing most of the transient energy to flow along a relatively harmless, prepared path, in such a way that wind turbine components are bypassed. The three primary components of this prepared path are the air terminal, the down conductor, and the turbine ground. The second way is to use special devices at critical locations to shunt that portion of the energy that does not flow down the prepared path.

As discussed in Chapter 2, the air terminal (lightning rod) may be a special device designed to be a lightning strike attachment point. In some cases the entire outer surface of a wind turbine may act or serve as a strike receptor and conduct the current to ground. It is best that most of the lightning strike energy be conducted down the tower well away from the electronic components. This means electronics should be located away from such things as down conductors, tower legs, support wires, and the enclosing metallic supporting structure. To the extent possible, transient currents should be either far from electronic component containers or equally spaced around them. An increased distance means a weaker magnetic field. Equal spacing about the electronic component containers means cancelling of magnetic fields as shown in Figure 4.9 and discussed in Chapter 2. Shielding of electronic components will further reduce the effects of electric and magnetic transient fields. An ideal shield is a closed cylindrical solid conductive (often metal) housing structure whose outer surface would also serve to conduct the lightning transient to ground. Theoretically such a closed conducting structure has a zero internal magnetic field [7].

At ground level, grounding rods, grids, buried rings, etc., are used as described in Chapter 2. The transient current should be dispersed well away from electronics equipment and the associated data, control, and power lines.

Shunting devices include arresters, relays, drainage inductors, and suppressors. They act on the principle that the impedance of the desired flow path is lower than the impedance of the path to be protected. Control over all potential transient current paths must increase as the distance to the fragile electronic components decreases. A transient-secure electronics environment must be obtained during the lifetime of each potentially damaging lightning transient.

A series impedance is required for a shunting device to limit voltage. The magnitude of the series impedance is extremely important. The relationship between the series impedance and shunting device is illustrated in Figure 4.10. Sometimes the series impedance may consist of the resistance and inductance of the existing wiring. At other times additional inductance and/or resistance is added to insure that adequate voltage limiting action is obtained with the shunt protector.

Lightning arresters usually refer to devices that will drain off energy at relatively high voltages and currents. These devices may be air-gapped carbon blocks, air-gapped copper, special gas enclosed gaps, etc. Such devices take many microseconds to operate and may maintain hundreds of volts across the device even after device conduction has started.

Relays are sometimes wired into the system so that above a specified voltage, the relay will shunt current flowing down the lines. Relays are generally very slow acting and are utilized more as a device to protect from a continuous high voltage on a line than from a short transient. For example, this could happen if a power line accidentally falls across a low voltage communications line and remains there.

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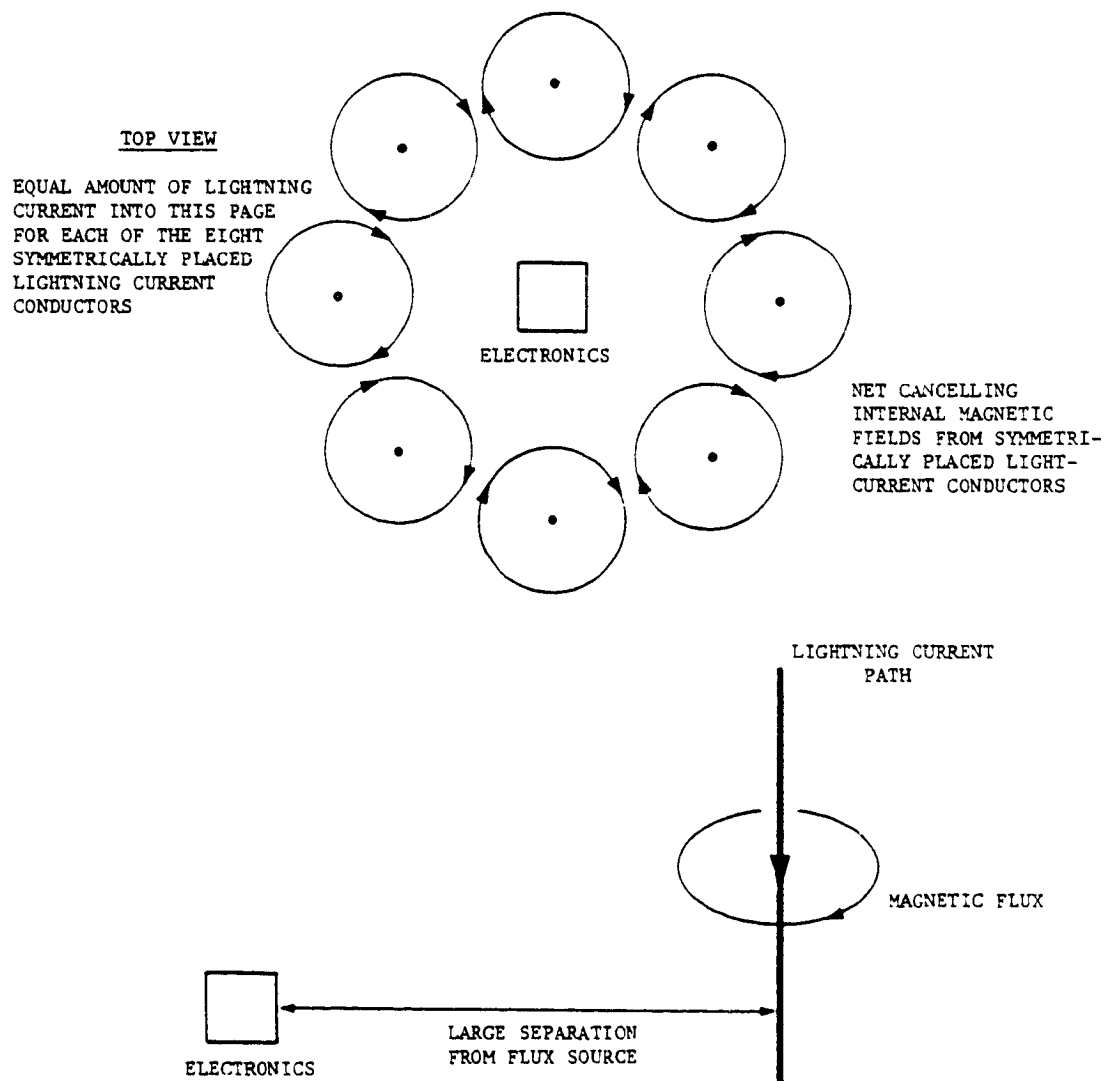


Figure 4.9: Reduction of Magnetic Field Coupling to Electronics.

Drainage inductors across a line that normally handles a relatively high frequency signal will provide a shunt for a much lower frequency content lightning strike or dc voltage on the line.

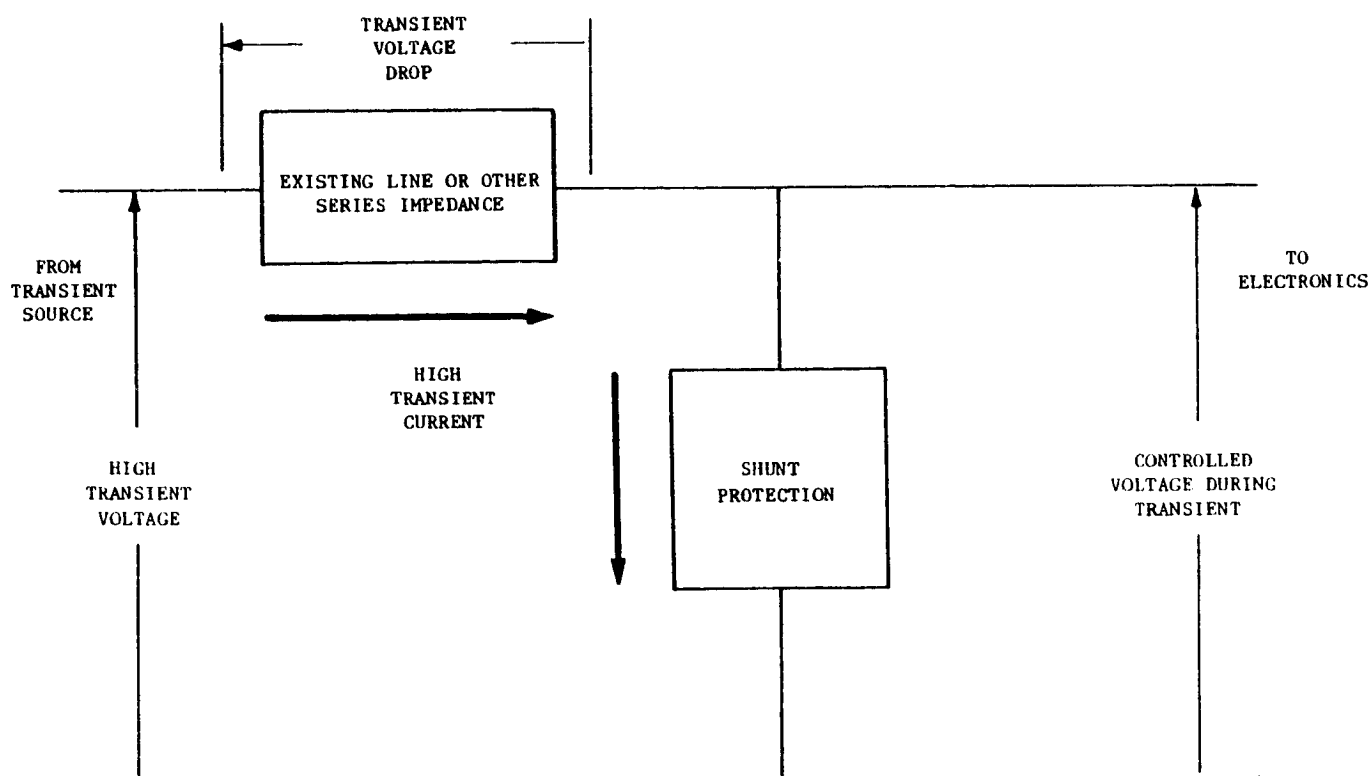


Figure 4.10: Dropping A Transient Voltage
Using Series Impedance and Shunt Current Protection.

Suppressors, a type of arrester, generally refer to devices such as gas tubes. Faster acting devices, in order of increasing speed of action, include varistors (for example the Metal Oxide Varistor, MOV [8]), zener diode, and special transient suppressor diode called the Transorb (TM) [9]. In general, the faster acting the device, the less energy it can handle. Another factor in locating protective devices is the rate of propagation of the electromagnetic wave throughout the electronics. Because of both power and propagation effects, the fastest devices are placed closest to the component they protect.

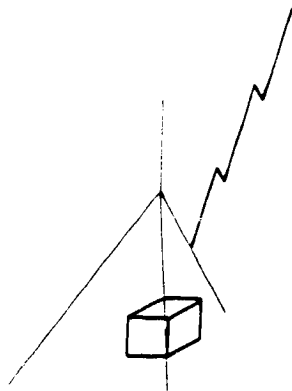
4.2.2.2 Isolation for Protection

While shunting a transient provides a lower-impedance path, isolation is just the opposite. Isolation techniques make the impedance higher for the transient energy in directions or along paths the transient should not flow.

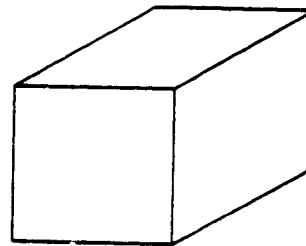
This impeding of the transient energy flow can be considered from the electromagnetic field or electric circuit viewpoint.

Radiation Shielding: When an electromagnetic field is impeded, the action is usually called shielding. The shield for a field will be an actual covering placed around the shielded region. This is not to be confused with a shield wire which is one or more wires placed between a protected region (usually power transmission lines) and the direct lightning strike from the sky. This latter use of the term shield describes a wire used to shunt lightning transient energy to ground in a conduction mode. See Figure 4.11. Shields must impede both the electric and magnetic fields, use multiple layers, account for field frequency, and not leak [10].

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WIRES SHIELDING AN ENCLOSURE
FROM THE CONDUCTION OF A
DIRECT LIGHTNING STRIKE CURRENT



AN ENCLOSURE SHIELDING THE
CONTENTS FROM LIGHTNING
STRIKE ELECTROMAGNETIC
RADIATION

Figure 4.11: Shield Wires and Shield Enclosure.

Electric field shielding depends on surface charge becoming distributed on the shield so as to intercept the electric flux generated by external electric charges. Magnetic shielding depends on the alignment of magnetic dipoles in the shield so as to cancel the magnetic field flux lines coming from external current flows or magnetized external sources [7,11].

Usually with appropriate materials and careful construction, about 40 dB or more of shielding may be obtained from each layer of shield [12]. If conductive paths exist between shield layers, they behave as a single layer. If a shield is desired in just a particular frequency region, it may be possible to have connections between shields at other frequencies. But care must be taken that multiple period effects do not nullify the shield for long lasting transients. Two totally isolated shields, one inside the other, each providing 40 dB of shielding would provide 80 dB of overall shielding.

$$\text{dB} = 10 \log P_1/P_2$$

where P_1 is transient power outside the shield, and P_2 is transient power inside the shield. Each shield layer must be separated from other layers for the frequency range of shielding. If these shields are connected by a low impedance path over some frequency range, charge will distribute between the two layers. The two shields will be degraded to a single shield in that frequency range.

Generally, shields have a greater effect as the frequency increases. This is not totally true when there are openings in the shield, or when the shield is a mesh. If the shield has non-homogeneous resistivity in dimensions that are small relative to the dominant wavelengths of the transient, then the shielding effectiveness can be greatly reduced.

When openings are not electrically sealed, energy may leak into or out of the break in the enclosure compromising the shield layer. Dielectric insulation between layers must be adequate to withstand the expected maximum potential difference between the shield layers.

Transient Conduction Reduction: Increasing the circuit impedance to the transient energy impedes the transient current flow in the electronics. This is done either by capitalizing on the difference in frequency spectra of the transient and the desired signal, and/or deactivating and isolating the circuit for the duration of the transient. Filters, optical links, fuses, and circuit breakers are three components that may be used to impede transient energy.

The lightning spectrum covers a wide frequency range. Filters may be placed in the lines to offer a low impedance to the signal or power spectrum while excluding most of the transient spectrum.

Carrying the impedance concept even further, signals can be converted to light frequency spectra and transmitted along an optical fiber. Optical fibers have a very high impedance to dominant frequencies in the frequency spectra of a lightning transient.

A fuse is a portion of a circuit which after certain conditions are satisfied will have an altered conductivity. Current limiting fuses may change from a low to a higher impedance after prolonged excessive current. Other fuses may open completely providing no further current flow unless the fuse arcs over with very high transient voltages. The use of a fuse to provide something relatively cheap to burn up instead of a more expensive

electronic or protection component must also be considered. Fuses are extremely slow devices when compared to zener diodes, but may be faster than the movement required by a circuit breaker. However, the circuit breaker is usually reusable and may even be automatically reset after the transient is over.

4.2.3 Maintainance of Data Integrity

Shunting of transients, while isolating the electronic components from damage, will often cause interruptions in the flow of signals and power between electronic subsystems and the connected sensors, controllers, and systems outside the wind turbine facility. Electronic signals, which provide crucial or life-dependent control actions, must be checked for both loss and possible error. Error correcting codes, multiple transmission of data, handshake arrangements, etc. must be a part of the control system design.

When a turbine system does fail, the data gathered by the sensors may provide valuable clues as to the cause. Important data about the wind turbine failure should be protected from loss caused by lightning transients. This means the wind turbine designer should protect not only the data portion of the system, but also the data storage portion of the system from lightning transient.

4.3 RECOMMENDED PRACTICE

The exact details (such as where shields of what thickness material and shape are located, what sizes and types of shunt protectors should be located at what locations etc.) of designing to reduce the effects of lightning transients become intimately dependent on the details of the specific wind turbine to be protected. Protection from lightning transients should be considered in the conceptual stage of the wind turbine design, since add-on protection may be difficult and/or expensive [13]. The final section of this chapter presents recommendations on how the wind turbine designer should treat the following nine areas to minimize lightning transient damage to electronics.

- o structure,
- o electronic subsystem enclosures,
- o power supply,
- o signal and control lines,
- o electronics circuitry itself,

- o computer subsystem,
- o sensors/transducers,
- o actuators, and
- o telephone lines.

4.3.1 Structure

Structures capable of conducting lightning current are recommended. The structure can serve as the primary down-conductor for a direct lightning strike and as the first stage of shielding for the electronics and/or cabling.

4.3.1.1 Tower

Use of piping for the tower legs, with the cabling inside these legs, or a large hollow metallic support with the electronic equipment housings located inside the tower is good transient protection design. More on this subject is covered in Chapter 2.

4.3.1.2 Equipment Rooms

Electronic equipment rooms should be located so that the magnetic fields produced by direct lightning strike conduction are minimal. As shown in Figure 4.8 equipment rooms should be placed in the center of the down conduction region. For added protection rooms should be placed inside a solid conductive outer covering [14]. To obtain another layer of shielding, electronic subsystem rooms should be dielectrically isolated from the outer conductive structure so that no common electrical connection exists between the outer structure and the conductively sheathed electronic equipment room. This makes the equipment room covering a topologically distinct shielding layer from the tower structure. This insulation of the shield is required to obtain another layer of shielding for transient electric field reduction.

4.3.2 Electronic Subsystem Enclosures

To protect electronic equipment from lightning damage it is recommended that at least two levels of electric field shielding are utilized. At least 40 dB of shielding should be obtainable from each shield layer. This would reduce an 8,000 volt per centimeter electric field to under 0.8 volts per centimeter. One or more layers of Mu-metal may be used to reduce the magnetic field if it is necessary to locate sensitive electronic components asymmetrically near a direct strike down conductor. In practical situations,

shielding imperfections must be considered. Major factors which influence the shielding effectiveness include: the material used to make the shield; workmanship during assembly of the shield; the method used to join pieces of metal making up the shield, such as welding; the design of shield enclosure doors, gaskets; the method used for cable and mechanical penetration; grounding and shield integrity.

4.3.2.1 Material

Both solid and meshed material with high conductivity and/or permeability can be used. Solid wall enclosures provide more effective shielding than meshes or screens. Among the most cost-effective shielding materials are sheets of cold-rolled steel and Mu-metal [12]. The main disadvantage of cold-rolled steel is its weight. The shielding enclosure may be constructed of materials such as copper screening or galvanized after-weave hardware cloth.

4.3.2.2 Assembly and Fabrication

The least expensive form of metal joining is to provide some type of pressure contact at the joint. Pressure can be obtained by nailing folded overlapping shielding material to a wooden strut. This method of joining seams will generally provide protection in the order of 30 to 50 dB [12].

Higher performance can be obtained by using prefabricated panel-type enclosures. Solid-wall bolt-together enclosures attenuate external fields in the order of 60 to 80 dB depending on the number and tension of the bolts [12]. The best shielding performance is obtained using welded joint cold-rolled sheets or Mu-metal panels. Welded seam enclosures can attenuate external fields in excess of 100 dB [12].

4.3.2.3 Doors

Shielding usually decreases in the vicinity of a door. The problem comes from a reduced electrical continuity between the door and the enclosure. Resilient fingerstock made of flexible brass fingers attached to the door can increase this electrical continuity. The fingerstock should be installed so a wiping action will occur when the door is opened or closed. Long term shielding performance can be improved by using multiple rows of fingerstock, placed in recessed slots. Recessed slots will reduce the damage to the fingerstock caused by dirt and abrasion [12].

4.3.2.4 Gaskets and Seams

Any type of corrosion between the joints of conducting metal sheets will reduce the attenuation of a shield. It is important to keep the electrical mating surface of nonwelded joints from corrosion by plating with tin, gold, palladium, platinum, or silver. Adequate pressure must be provided continuously along the mating surfaces. This can be done using a linear array of bolts with about 100 lb of force per linear inch. These bolts must be retightened occasionally to maintain pressure at the joint. Electromagnetic gaskets are made of conducting material which will deform to the irregularities at the seam joints. Such gaskets are very useful in reconditioning leaking shield joints [10,12].

4.3.2.5 Cables

Communication and power supply cables must be electrically hardened. A metallic continuous solid-wall cylindrical outer conduit is good practice. This outer shield should be as thick as possible and should not be used as a signal return path. Co-axial cables and/or twisted pairs are run inside the conduit. Pairs are twisted so that on average the same, i.e. a common, voltage is induced in both wires. This common voltage can be eliminated from signals carried as the difference in voltage between the wires by use of a differential amplifier on the receiving end of the cable [10,12].

4.3.2.6 Grounding Precautions and Shielding Integrity

Ideally a shield enclosure would be totally isolated. However, total isolation of the shield is not possible since penetrations must exist for things such as plumbing, waveguides, and grounding conductors. If not done properly, these penetrations will seriously degrade the shield.

Grounding conductors, waveguides, and plumbing should not be allowed to penetrate the shield without electrical contact with the shield. Power and signal conductors must be isolated or connected to the shield through a surge arrester or filter. These techniques for maintaining shielding integrity are illustrated in Figure 4.12 [15]. Screens or other electromagnetic shielding material must be placed over any openings in the enclosure needed to provide such things as air ventilation [10,12].

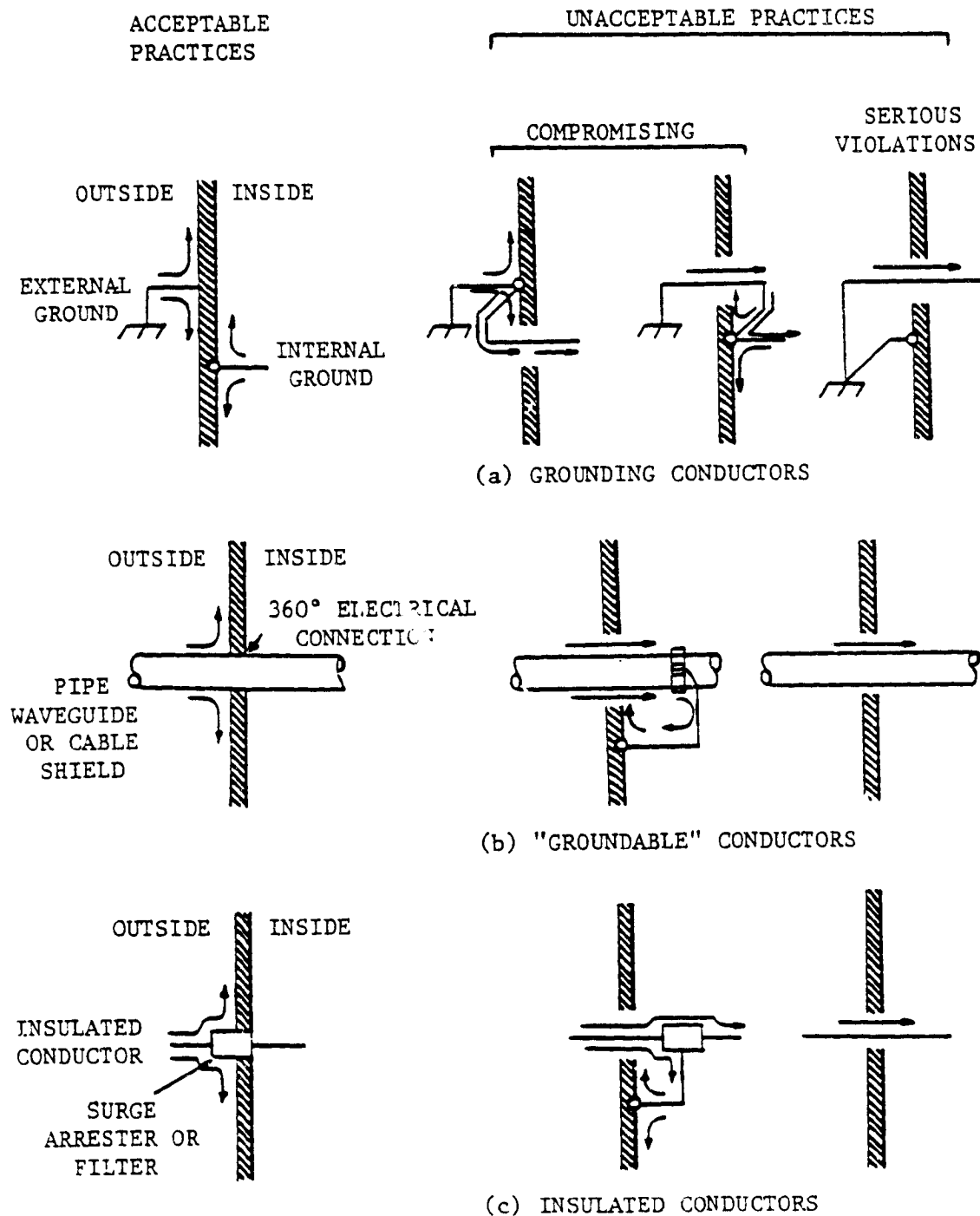


Figure 4.12: Ways to Maintain and Violate Shielding Integrity
With Conductor Penetrations [15].

4.3.3 Power Supply Considerations

Since the extensive power line network is often struck during a storm, it is one of the most likely sources of lightning transients to electronic equipment. For this reason the power supply is the most likely link for transients into the electronic equipment.

4.3.3.1 Dedicated Power Line

A dedicated power line is one which runs only from the power distribution box to the electronics subsystem. This line must not run to other equipment within the facility. At least three reasons suggest this as a good practice. First, inductive reactance transients are generated by other equipment such as motors, switches, and contactors by their inductive activity. It is best to keep the environment for the electronics as quiet as possible by isolating it from this noise-producing equipment. Second, this other equipment, depending on the location within the facility, also increases the exposure of electronics equipment at the site to sources of local lightning transient conduction. The third reason is that loops must be avoided. All wiring must, to the maximum extent feasible, use a tree configuration. This is the only way to have wiring within the facility that will not be a potential for transient modification of loop voltages. This loop may be one that exists all of the time, or may be one that is created during the lightning transient by arcing.

Generally it is more expensive to create a dependable low transient level power line. Most equipment does not need the degree of quiet power required by the electronics. Thus, the expense of providing quiet power should be restricted to the equipment that must have it, such as the electronics.

4.3.3.2 Power Line Side Transient Suppression

Before the power has entered the wind turbine facility, transient suppression devices such as lightning arresters have been provided by the electrical utility. Still needed is a device close to the power supply input which will prevent extremely short-duration spikes from entering. These sharp high-frequency spikes, if allowed to enter the power supply, may then propagate to other places in the electronics subsystem by conduction, radiation, and/or capacitive and inductive coupling.

Special power line transient suppressor equipment for electronic equipment has been developed. Such suppressors will shunt excess current to ground with a very fast response time and maintain nominal operating voltage at the power supply input terminals. A typical transient suppressor can handle 2,000 to 3,000 watts of peak power for a duration of milliseconds and with a response time of 5 nanoseconds [16].

A study conducted by Richard Odenberg [17] concluded that the placement of the transient suppressor is extremely important. The suppressor should be installed so that the lead length from the suppressor to the load under its protection is made as short as possible. The effectiveness of the transient suppressor is inversely proportional to the length of the connecting leads.

4.3.3.3 Electronics Side Suppression and Isolation

Faster suppression at a lower power rating is required on the electronic component side of the power supply. For systems which have a dc supply feeding a number of subunits, such as printed circuit cards, a higher relatively unregulated dc voltage can be fed to the printed circuit (p.c.) cards in common. The supplied dc voltage is then regulated down to the desired voltage at each card. In addition a transient suppression device should be on each card with the regulator. The margin voltage for regulation, also is a margin which allows clipping of any voltage fluctuations received between the main power supply and the p.c. card. If a transient successfully enters the interior of the power supply, on-card transient suppression minimizes the risk of destroying components on every p.c. card. Although redundancy generally increases as devices are placed in parallel, this is true only if a portion of the devices can carry the entire load. Hence a single suppression device failure should not cripple the system. When Transzorb and MOV devices fail, they generally fail in the shorted mode [9,18]. A slow blow fuse in series with the suppressor device is suggested to prevent failure of the entire unit because of the shorting of a suppressor on one p.c. card.

4.3.4 Signal and Control Line Considerations

Signal and control lines must not be permitted to take lightning transient energy into the relatively delicate electronics component environment. In addition it is often impossible to prevent many local ground loops inside the electronics subsystem enclosures. That is, the tree structure of Chapter 2 may be impossible to implement from an electronic subsystem requirement perspective because of timing and propagation delay constraints. For such situations the electronics environment must receive the very minimum exposure to electrical transients.

Signal lines are usually less rugged than the control lines, especially analog input sensor lines. During a direct lightning strike to the wind turbine tower, it is the goal of the lightning protection design to seal off the electronic subsystem boxes from the harsh outside transient world and to prevent the external wiring from being destroyed. After the transient passes, operation can be quickly resumed.

4.3.4.1 Transient Suppressors

Transient suppressors are placed both in series with shields and as shunts at the ends of cables. Suppressors provide for both shunt protection of electronics and augment the transient current path. Suppressors become low impedance when the voltage exceeds a specified threshold. To prevent destruction of the cabling, suppressors in series with the shields are used as described in the next section. Shunt use of the suppressor is to seal off the electronics enclosure from transient energy attempting to enter from the outside via the cable or wiring. Cable transient suppressors should either be located just outside the electronics enclosure, or inside an entry box attached to the electronics enclosure.

4.3.4.2 Shielding

Shields are often connected to local ground at only one end to minimize the risk of a ground loop. For lightning protection, the shield may provide yet another path to help get rid of excess lightning transient energy. Analysis of the electrical properties of cables subject to lightning reveals possible transient reduction by multiple point grounding of cable shields [10]. It is recommended that cable shields be grounded at multiple points through reverse biased diodes that will permit large voltage currents to flow along the shield while acting to prevent instrumentation level voltage loops from occurring. Additionally, the usual use of twisted pairs with differential line receivers and low-impedance drivers, respectively, to cancel and minimize noise pickup, also helps to reduce lightning transients. Series diodes are placed as shown in Figure 4.13.

Shields must not be violated by the breakdown of a shield suppressor. Sufficient dielectric must be present between shield layers to prevent such a breakdown. The shield suppressor must take energy to the system ground and not to the next interior level of shielding. Separate layers of shield topology must be maintained. This may require an inline transient filter on cables, which must be located between shield layers. An alternate means of maintaining shield separation is to use optical fibers. Optical fibers may be used for the transmission of data between shield layers. To a much lesser extent power may also be transferred between layers using optical fibers.

4.3.4.3 Optical Isolation Techniques

An optical communications system can serve as a means of electrically isolating one electronic subsystem from another. An optical fiber, used to link the communication transmitter and receiver, provides a nonconducting path between the electronic subsystems. However, even this optical fiber cannot totally isolate electronic circuitry from lightning transients.

The essential elements of an optical communication system are shown in Figure 4.14. The transmitter source is usually a solid state injection laser

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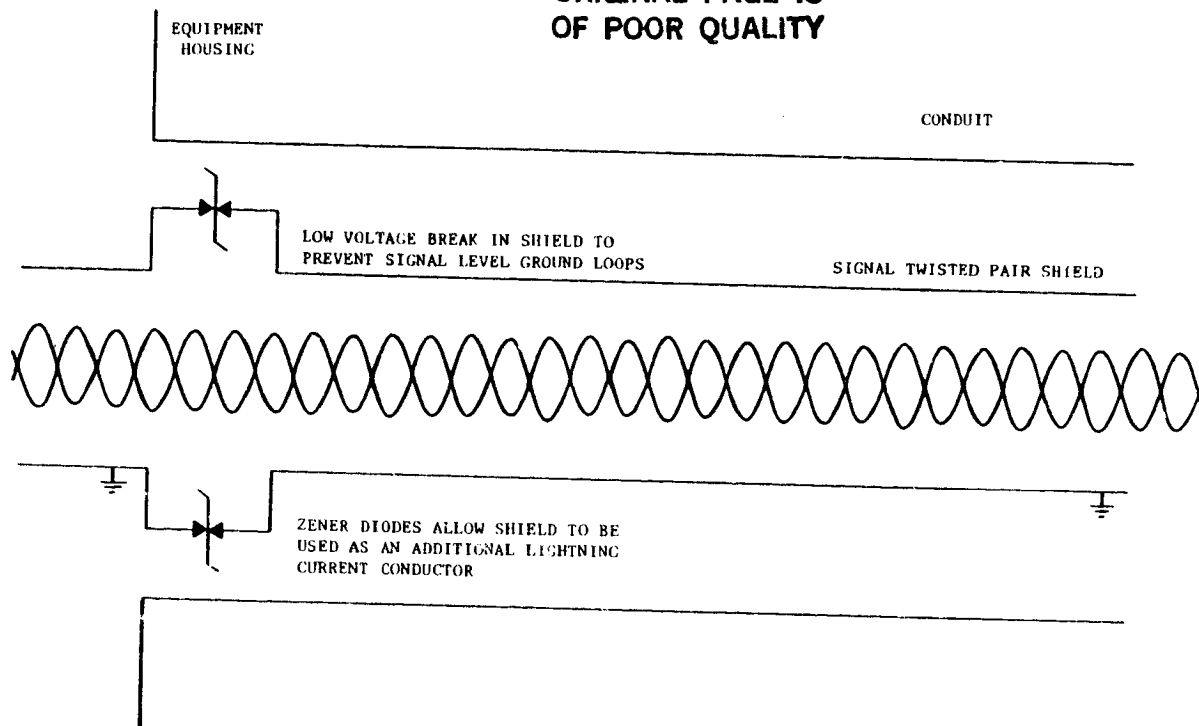


Figure 4.13: Using The Cable Shield to Carry Lightning Transient Current.

or high-radiance light emitting diode. The main component in the receiver is a photo-detector. The operating capabilities of any lightwave communication system are determined by:

1. the loss and dispersion characteristics of the fiber and any terminations;
2. the average amount of light power which can be injected into the fiber; and
3. the sensitivity of the photodetector [19,20].

The nonmetallic optical fiber used for signal transmission is a light waveguide of dielectric material. The electromagnetic fields generated by a typical lightning current waveshape are of a frequency that won't enter the fiber optics. However it may be possible that the bright visual flash associated with arcing could intrude into this light waveguide. If fiber optics are less likely to have data contaminated during transmission they may require less sophisticated error detection techniques. This could mean a decrease in total cost of data links. Also an optical transmission system needs no return line and the signal is not referenced to any particular ground

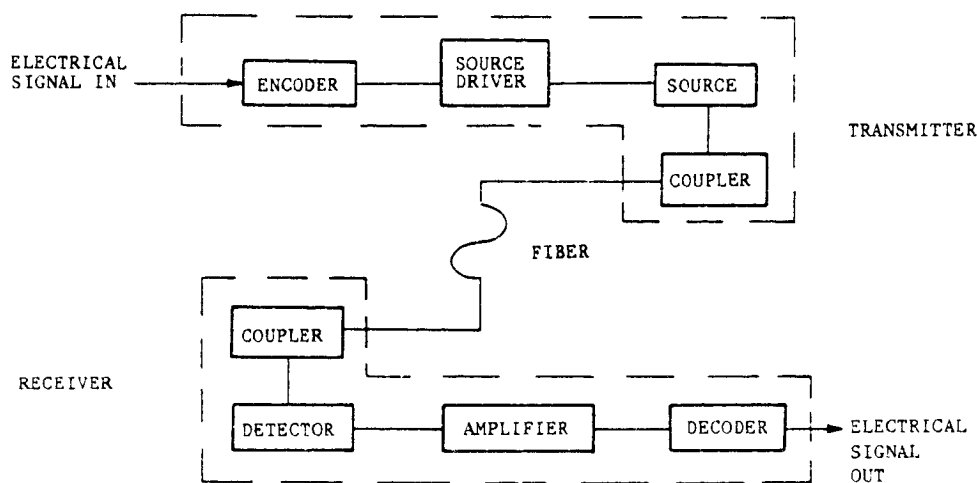


Figure 4.14: Optical Communication System.

potential. Hence data transmission can be achieved without regard to ground level.

A number of modulation techniques can, theoretically, be used to impress the desired information on the lightwave. Digital modulation of the light source coupled with square-law detection represents the most practical scheme. The desired information is carried by the optical fiber as a series of light pulses which are detected and demodulated at the receiving end of the system. Pulse code modulation (PCM) is an ideal candidate for optical data transmission since the information is contained within the presence or absence of light as opposed to information being contained in the magnitude of the detected light. Pulse position modulation (PPM) is attractive for analog signals because of low duty cycle. High peak power lasers can be used and noise immunity is achieved, as with PCM, by expanding the bandwidth of the baseband signal to take advantage of the broad band capability of the fibers.

The total optical communication system is not completely free from external interference. Although electromagnetic energy does not enter the system through the fiber transmission line, it can enter by way of the transmitter/receiver electronics. This generally manifests itself in the form of interrupted data bits and noise interpreted as data by the receiver. Hence, it is necessary to provide proper shielding and grounding to protect the photodetector and associated electronic circuits [19,21]. The opening through which the fiber enters the receiver needs to be small compared to the wavelength of the highest frequency component of lightning.

Due to the numerous control and monitoring functions which must be carried out by the turbine control processor, a large number of transmission lines are required to sense system parameters and to transmit action signals. A single, large bandwidth, optical fiber transmission line could easily handle the required data transfer. Figure 4.15 illustrates a system which would require a single optical fiber to transmit information to the control processor. This same fiber could also be used to transmit control information from the processor to various electromechanical systems on the ground and in the nacelle.

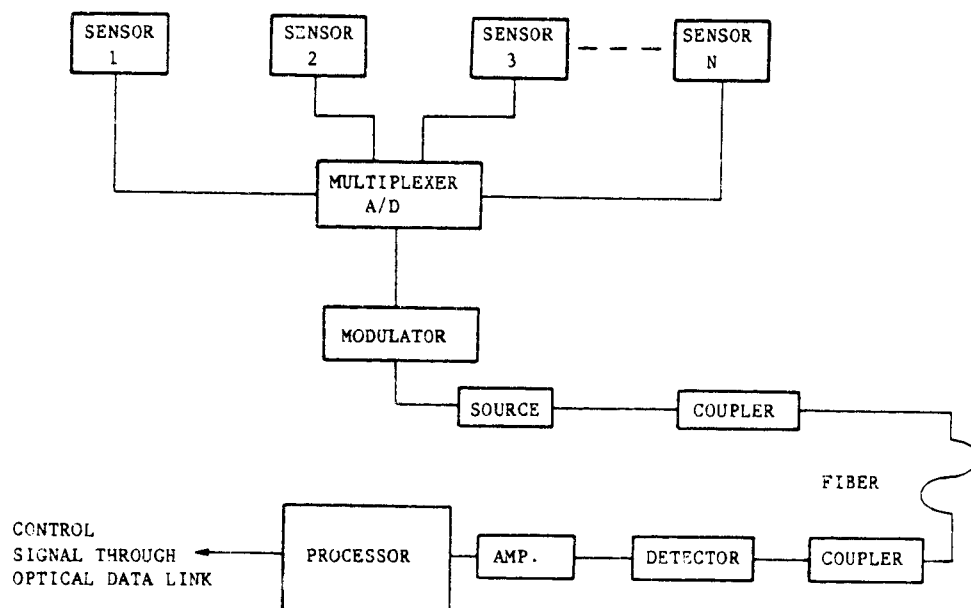


Figure 4.15: Single Fiber Multiplexed Optical Communication System.

The electronic devices required to perform the various signal processing functions in the transmitter and receiver sections require relatively small amounts of current. It may be advantageous in some cases to use battery packs to supply dc biasing currents and voltages. The battery supply should be placed in the same enclosure as the injection laser, LED, or detector circuitry, requiring perhaps once a year replacement. It may also be possible to transmit the required power through fiber optics.

Most large horizontal-axis wind turbines will bring signals from the nacelle through slip rings. This is necessary because of the 360 degrees rotation capability of the nacelle for proper orientation with respect to the wind direction. "Optical slip rings" do now exist, so that no problems should be encountered if full 360 degrees rotation of the nacelle is required. Although optical fiber cables are as flexible as most cables, they could not

withstand multiple twists. If a limited rotation of the nacelle is allowed, no slip ring assembly would be required and the twisting of the optical cable could be accommodated by a large "slack loop" in the cable from the nacelle to an optical cable conduit, or to a tie point at the tower.

4.3.5 Hardening Techniques for Electronic Circuitry

Analysis must be performed at the circuit level to determine the characteristics (magnitude, duration, waveshapes, etc.) of the smallest signal that will cause the burnout of the most susceptible component contained within the circuit under consideration. Individual component damage level is a function of frequency. Therefore, for pulsed input signal transients, the spectral composition must be known to determine the pulse power that will cause permanent damage (although soft failures may also result in overall circuit malfunctions). The validity of a damage threshold analysis requires an accurate data base of actual and rated damage levels. This data base allows for the complete characterization of the pulse-power response of all electronic components [22,23,24].

Typical lightning-induced signals are composed of high-amplitude, short-duration transients which result in a nonlinear response by the individual component or particular circuit [25,26]. These responses are not defined by existing device models, thus requiring the examination of each component in order to develop appropriate models. A detailed damage-threshold analysis of a circuit may be performed by utilizing the procedure developed for Electromagnetic Pulse Protection [27].

Any circuit node which is exposed to a lightning-induced transient must be analyzed to determine its damage-threshold level [25,26]. An examination of wind turbine control/instrumentation electronics indicates that numerous exposed ports are possible. Each must be analyzed separately and in combination with other circuit ports to completely characterize the susceptibility of the electronic circuits/devices to lightning transients.

When analyzing multi-port combinations it is necessary to determine the amplitude and phase characteristics for the transient signal sources. Unless a relationship between both the phase and amplitude of two or more transients can be defined, an infinite number of combinations of these two parameters can cause a device failure. Given the proper phase/amplitude relationship, a single combination of transient input-port voltages will determine the failure thresholds for the circuit or device.

For lightning-induced transients the exact nature of the signal cannot be determined in a manner which will allow the designer to set exact responses of a circuit from induced and direct effects [22,23]. Therefore, one is forced to perform worst-case analysis in which the highest or most potentially damaging circumstances are assumed to exist. An in-depth Failure Mode and Effects Analysis (FMEA) of component parts may single out components most susceptible to damage. Such analyses are performed utilizing the best possible lightning models and estimation of signal transient voltage/current.

Once lightning parameters have been determined, it may be possible to reduce the multi-port analysis problem to one of simpler proportions. In most cases, one of the transfer impedances will dominate, in which case the multi-port nature of the circuit response to external excitation may be ignored and the analysis may be conducted considering only the dominant impedance and transient source.

Before damage analysis of a circuit or component can be performed, the component's power profiles, $P(f)$, must be known [27]. Several known data bases contain this information [22,23,24]. The development of models that will predict the failure levels of junction semiconductor devices have commanded a great amount of attention [27,28,29,30,31,32]. This fact is, of course, due to the susceptibility of semiconductor devices to pulse power burnout, which identifies these devices as the most critical components in any circuit.

The Wunsch model has been widely viewed as the most general model available for transient response damage [22]. In this particular model the pulse power required to burn out a semiconductor junction is related to the pulse width and has the formula:

$$P_j = K_r t^{-1/2}$$

where P_j is the required pulse power for failure of the junction and t is the pulse duration. K_r is referred to as the Wunsch constant. For a particular device it is dependent upon device geometry and material.

The model was originally developed and evaluated for devices operating at reverse bias and subjected to pulse widths between 20 and 50 nanoseconds. To obtain a value for the current to produce a junction failure, I_j , the pulse power, P_j , can be divided by the reverse bias breakdown voltage to give:

$$I_j = \frac{P_j}{V_{BD}} = \frac{K_r t^{-1/2}}{V_{BD}}$$

where V_{BD} is the junction breakdown voltage in the reverse bias direction. In order to determine the device power, P_D , necessary to produce failure, bulk resistance heating effects must be included.

$$P_D = I_j V_D = P_j + P_B = I_j V_{BD} + I_j^2 R_B$$

where V_D is the voltage across the device, P_B is the power dissipated in the bulk material, and R_B is the bulk resistance. For many devices the bulk resistance may be neglected, thus simplifying any experimental determination of device constants.

The power necessary to produce junction failure under forward-bias conditions can be approximated as:

$$P_F = K_F t^{-1}$$

where K_F is called the forward bias damage constant [27]. When a semiconductor junction is operated under forward-bias conditions, large current variations are possible, resulting from extremely small changes in the forward voltage. For this reason, forward-biased devices may be more susceptible to failure than reverse-biased junctions.

For a forward-biased junction that is operated near failure, the current will be large, with the device power approximated by,

$$P_D = I_j^2 R_B$$

The power dissipated in the junction will be small in comparison with the bulk resistance power dissipated within the device.

In the forward bias state, the source will appear to resemble a constant current due to the small value of the bulk resistance. Under these conditions the power will be proportional to the bulk resistance. This means that the value of R_B forward be known through experimental or estimation techniques. The bulk resistance term in the power models takes on varied importance depending upon the biasing conditions of the particular device applications. The bulk resistance of a forward biased device is normally small (0.1 to 10 ohms). A higher value for R_B forward is associated with low-power devices which have small junction areas and limited current capabilities. The lower forward bulk resistance values are normally associated with high power devices which can handle large currents and therefore require large junction areas.

Devices which are operated under reverse-biased conditions typically have bulk resistance values between 100 and 10,000 ohms or more. Under these bias conditions a particular device with a low bulk resistance will have low breakdown voltage while a high bulk resistance will be associated with a large breakdown voltage. It should be emphasized that the information above is general in nature and that each device has a particular set of parameters which are dependent upon the device type, material, doping, configuration, contact material and geometry, etc. To summarize: when performing a failure-threshold analysis on low-power, low-breakdown-voltage devices operated under pulsed reverse-biased conditions, the bulk resistance can be neglected. When analysing high breakdown voltage devices which are pulsed in the reverse direction and junctions pulsed in the forward-biased direction, the bulk resistance term must be taken into account.

A very thorough and complete description of the exact procedures, including example problems, for transient failure analysis of circuits and devices may be found in references [22,23,24,27]. Although the material presented within these referenced works is directed toward electromagnetic pulse electronic analysis, the same procedures are directly applicable to electronic circuit/device lightning-induced transient failure analysis. The expense of a complete analysis may be justified if a large number of wind turbines are produced.

4.3.6 Computer Subsystem Considerations

The computer subsystem in the modern wind turbine system is the heart of the system monitoring, decision making, and control. It is imperative to provide automatic mechanical failsafe capabilities to prevent disastrous wind turbine actions. Increasingly, the electronics control is also providing for new important additional turbine safety activities. Decisions which involve complex combinations of conditions are natural areas for automatic electronic safety intervention. Decisions such as those associated with power synchronization and start-up procedures are usually performed by electronics control.

Some means of computer subsystem verification is essential, for both the hardware and the software. Transient activity may damage just a portion of the data, program, or hardware. This damage may go unnoticed until some crucial situation arises. Thus, the system must be inspected periodically using an external or internal method. Self checks by the computer may satisfy much of this requirement.

4.3.6.1 Error Detection

Errors may be detected in digital data by the use of codes. A parity bit may be added to each digital word. Even better, check sums may be added to groups of digital words. Error correcting codes permit automatic correction of the data when one or a few bits are in error. Multiple storage of the data will permit retrieval of the data when one source has been corrupted. Redundancy may be extended to multiple crosschecking computer systems. The software may crosscheck sensors or check instrumentation readings against reasonable limit values to be expected. Automatic checking of values for reasonable ranges is also possible and desirable. Crosschecking of related types of readings for concurrence is another approach to error detection. The error priorities and actions to be taken must be stored in the system memory. Some errors may require the shutdown of the wind turbine system. For other errors a provision for requesting human intervention may be sufficient.

Computer integrity, upset, and destruction are important considerations in lightning protection design. Wind turbines normally employ software which has progressed beyond the developmental stage where the programs are frequently changed and thus kept on disk or tape for loading into RAM. Instead the programs will probably reside in ROM or EPROM or EEPROM. Without destruction of the storage chip it is hard to degrade data in these more permanent forms. Provisions must be made for periodically checking the integrity of the system software and hardware. A comparison of software sets is one means of determining software integrity. At least the critical portions of the software could be redundantly stored for checking. Periodically, a self-check routine should be run on the machine. For very high reliability operations, this can be done continuously with jumps to routines which perform other useful work amidst the certification checks.

Data for wind turbine shutdown is important for protection of personnel and equipment. The critical data must be carefully handled to prevent costly malfunction of the turbine. Sensor and computer generated data may be used for shutdown and control. All storage and handling of this data must be done with a high degree of reliability. Thus the use of error correcting codes and, possibly, multiple processors for larger wind turbine systems is recommended. Monitoring data should be transferred on a periodic basis and during shutdown to a more permanent medium such as magnetic tape or disk, or via modem and communication link to a remote storage facility.

4.3.6.2 Data Retention

Power generation records must be kept, and the computer system which can monitor and calculate the power is a reliable and accurate device for doing this task. Other reasons also exist for the retention of data about the wind turbine system operation as discussed below.

The computer system can monitor an immense variety of conditions throughout the wind turbine system including vibration data, temperatures of large bearings, acoustic analysis, etc. Such data can be very useful in anticipating both mechanical and electrical component failures. In the event of a system shutdown due to lightning transients, it is important that long-term performance data not be lost. Memory devices for temporarily retaining sensor or productivity data include electrically erasable programmable read only memory (EEPROM), magnetic storage media, and battery backed-up random access memory (RAM). Such devices can hold a small amount of data placed there for some time span prior to and during failure. A sensor can read the system line voltage and initiate a write command to preserve key data. This can be done before substantial charge has been used from the computer filter capacitors in the power supply. Alternately, an uninterruptible power source (UPS) can provide computer power for some minutes or hours after wind turbine failure.

While performance monitoring may best be used to prevent wind turbine failures, performance data collected during a failure can be extremely helpful in finding reason for the failure.

4.3.7 Sensors/Transducers

The sensors in the transducers of the wind turbine electronics subsystem sense thermal, mechanical, and electrical values. The total transducer then converts these sensed quantities into some electrical form that can be processed, more often than not by a digital processor. Some of these parameters, such as high wind speed, or excess strain on tower structure components, or excessive voltages due to electrical component failure are very critical for safety. Transients caused by lightning can destroy or degrade sensors.

4.3.7.1 Sacrificial

It may be less expensive to allow the sensor/transducer of a noncritical measurement to be destroyed than to attempt to build a unit able to withstand a direct lightning strike. This is especially true of those units located on top of the wind turbine where the large current of a direct strike is possible. Critical sensors/transducers can be provided in multiple locations to allow for the failure of one of the critical units.

4.3.7.2 Hardened

If it is desired to harden a sensor/transducer to withstand lightning transients, then the shunting and shielding techniques previously described would be applicable. However, protection must not degrade the performance of the sensors. An alternative to protecting an existing transducer is to design or select very rugged transducers. Such transducers would have the capacity to carry a high current, have no internal solid state devices which are sensitive to high voltage gradients, and have brush bypassing or strapping around any moving parts. Those units on the top of the wind turbine must be assumed to be expendable. Nonetheless hardening such instrumentation can provide protection against side streamers and the less severe main strokes.

4.3.7.3 Multi-located

Sensors/transducers can be placed at different locations on the turbine to reduce the probability that a single lightning strike will damage them all. For example, anemometers on the roof of a turbine nacelle should be placed as far apart as possible.

4.3.7.4 Information Overlap

Some sensors may provide data that, with some processing, can hint at or allow deduction of other conditions. For example blade settings, along with power output of the turbine, could allow an estimate of the wind speed. Thus, the retention of sufficient data to perform such diagnostic analysis is an essential goal of the system designer.

4.3.8 Actuators

Actuators tend to be more rugged than sensors. The drive electronics is able to withstand greater power surges than the sensor electronics. Even so, the extreme nature of lightning transients is sufficient to jeopardize the actuators. Arresters and suppressors should be used to bring the levels of transient power and voltage below the values that the actuators and the

actuator electronics can withstand. If the drive electronics is located close to the mechanical actuators, then the data from the command electronics will be vulnerable to corruption, and encoding and modulation to protect the integrity of this data must be used. Local isolation and protection of input from transients on the line must be provided. The local control must have a means of carrying on without the data for a few milliseconds to a second or longer while a lightning transient disrupts communications within the wind turbine system. A means of protection against local failures should also be provided. If the drive electronics subsystem is some distance from the mechanical actuators, then loop voltage changes due to a strike may be a problem on the connecting lines. Once again, even the larger drive voltages to an actuator are small when compared to those in a lightning strike.

4.3.9 Telephone Lines

Telephone lines are becoming increasingly important for the remote monitoring and control of sophisticated equipment. Monitoring and control will usually be through a modem rather than a direct-coupled line. The telephone usually provides a degree of protection from outside transients through an arrester. Additional protection for the modem using high speed suppression devices is also good practice.

In addition, the telephone company will also be concerned with the voltages that may accidentally be placed on the telephone line by the wind turbine system. Care must be taken with telephone lines at all power generating facilities by following all applicable electrical codes. Wind turbines are generally located at places with a high lightning transient exposure and it may be necessary to go beyond the protection called for in the existing electrical codes.

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Chapter 5

BLADE PROTECTION

5.1 INTRODUCTION

Lightning strikes that directly hit the wind turbine will probably attach to the blade. The damage occurring to the blade could cause excess structural damage. The blade and hub usually represent around one fourth of the cost of a large modern machine and may be the most expensive components to replace. The blade is not only the link between wind energy and the mechanical energy going to the gearbox, but could be a lightning link to all the equipment associated with the wind turbine. This chapter addresses protection of metallic and nonmetallic blades from lightning damage.

5.2 BLADE DAMAGE

Aircraft and electrical power industry engineers have had experience in dealing with lightning. Even though most aircraft lightning strikes are from cloud to cloud, similar protection techniques are applicable to ground based wind turbine blades. Most of the power industries' experience deals with surge protection of line transformer and other power equipment. Some of the work on tower protection and modeling is useful in evaluating blade protection techniques.

The book, "Lightning Protection of Aircraft" [1] is the source of much of the information that follows. Lightning strikes to metal aircraft wings illustrate what might be expected if a metal wind turbine blade sustains a direct hit. Composite materials that have been proposed in blade construction normally are poor electrical conductors and could be damaged if a lightning protection system is not provided. Fiberglass radomes with no lightning protection have been rendered useless and hazardous to flight when struck by lightning [1].

5.3 METALLIC BLADES

Both steel and aluminum will continue to be the major metals used in blade construction. Even though the metallic structure used in blades serves as a good conducting path, damage can still occur to metal blades. The damage that can be expected on metallic blades includes melting at lightning attachment points, magnetic stress, and pitting from arcing at discontinuities.

A discussion of melting at attachment points [1] indicates that it should be of little concern to manufacturers of metallic blades. Temperature rise of metallic blades carrying lightning currents is temporary and probably will not effect structural integrity.

Magnetic forces resulting from large lightning currents and certain blade geometries could cause damage such as permanent bending and/or fatiguing of the blade structure. Forces on bonding straps used to connect metal to metal can cause them to be damaged and also cause damage to nearby structures. These forces result from the interaction of current-carrying conductors and magnetic fields. The magnitude of these forces depends on the system geometry, current magnitudes and directions, permeability, and separation distance. For example, two parallel conductors, each carrying 50,000 amperes and placed 2 centimeters apart in air, will experience a force of 25,000 N/m (1,713 lb/ft). Bonding straps should have sufficient cross sectional area to carry lightning currents; they should be short; bends should be smooth and less than 45 degrees; and parallel straps should be sufficiently separated.

Arcing could occur around hinges and pivot points on a blade. The control surface pivot points on some blades such as the MOD-2 blade [2] could produce some arcing if in the position shown in Figure 5.1. There will continue to be tip or blade pivot points on large horizontal wind turbine blades. The use of bonding straps, and/or blade positioning procedures during a thunderstorm will aid in the protection of these pivot points.

Strike history and simulation tests will show whether or not engineering analysis is valid. Only minor damage is expected to occur to metallic blades, but tip lights, ice detectors, strain gauges, and other components attached to the blade are more apt to be damaged. Damage to these components can be reduced if lightning protection is designed into the instrument system.

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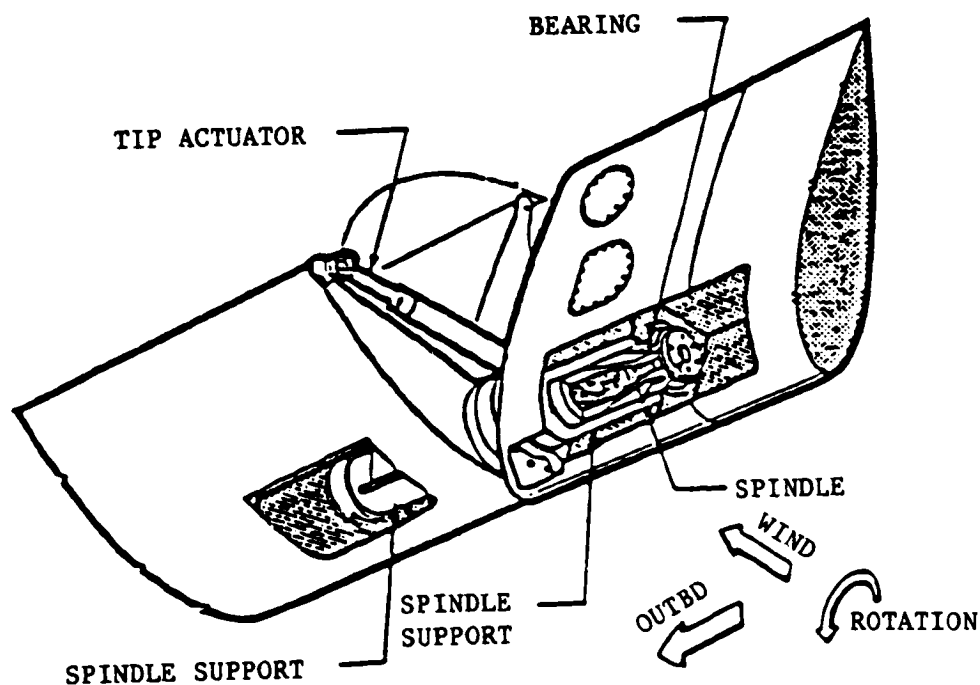


Figure 5.1: A Typical Tip Control Mechanism.

5.4 NONMETALLIC BLADES

Several nonmetallic blade structures have been considered for large wind turbine blades. Both fiberglass and wood composites appear to be viable alternatives to steel and aluminum, but because fiberglass and wood are both poor conductors, a direct strike to either could cause severe damage. Fiberglass radomes have been shattered by real and simulated lightning [1] when no protection was provided. It has been shown that epoxy-wood blades will be severely damaged if no protection is provided [3].

The following principle for providing protection to nonmetallic structures can be used for accommodating strikes to blades. By providing a good conducting path on the surface of the nonconducting blade, lightning currents will not flow inside the structure. This is shown in Figure 5.2. Five acceptable ways of providing an external conducting path are shown in Table 5.1. The comments on the table should serve as a general guide to those

considering protecting nonmetallic blades. Compatibility with manufacturing processes and other factors should be considered in the design of lightning protection of blades. Coordination with vendors of these materials is a recommended step before reaching a decision on the method of protection.

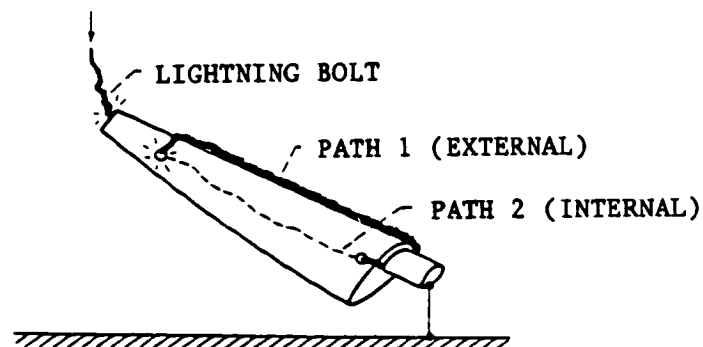


Figure 5.2: External Charge Transfer and Internal Streamering.

Nonmetallic blades may have some structural weight and cost advantages over metallic blades. Furthermore the television and communication interference caused by metallic blades is eliminated. However, tests have shown that both fiberglass [4] and wood blades [5] need some type of lightning accommodation system. Damage to a fiberglass blade on NASA's Mod-0 machine is shown in Figure 5.3 [6].

Bankaitis [3] points out that blade lightning protection systems must be:

1. capable of dissipating the energy imparted by a lightning strike without deleterious effects to personnel, structure, or instrumentation,
2. inexpensive to install and maintain,
3. compatible with the processes by which wind-driven turbine rotor blades are manufactured,
4. capable of withstanding repeated lightning strikes,
5. easily repaired in the field, and
6. noninterfering with television reception or navigational or communication equipment functions.

In meeting all these requirements the designed system shall not compromise the structural integrity of the rotor blade.

TABLE 5.1

Ways to Provide External Conducting Path

PRODUCT	METHOD OF APPLICATION	COMMENTS
Conductive Tape	Position as required apply pressure. Soldering or welding to metal surfaces.	Apply to the leading and trailing edge. Aluminum tape has been shown to provide protection on fiberglass blades.
Conductive Paint	Brush or spray.	Paint with silver content has worked on helicopter blades. Other metals or alloys used in paint will require testing.
Alumnized glass cloth or metal-glass cloth	Put in place and secure to blade using an appropriate adhesive or process.	More than one layer may be required.
Diverter Strips	Apply to blade non-conducting surface and solder or weld to metal surfaces.	Results should be similar to tape. The TV interference may be less, but the cost of protection may be greater.
Screen mesh	Apply adhesive to nonconducting surface and weld or solder to metallic surfaces.	Wooden blades have been shown to have adequate protection with this method. The screen was covered with epoxy and paint.

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BLADE NUMBER 1 AUGUST 11, 1982

PLUMBROOK, OHIO

Figure 5.3: Damage to Fiberglass Blade from Lightning Strike.

5.5 TESTING

In order to establish the validity of a lightning accommodation system a test program will normally be necessary. Guidelines for such tests are contained in the SAE Committee Report [7]. The test set-up used for a wooden blade is shown in Figure 5.4 [5]. The protection scheme for these blades is shown in Figure 5.5.

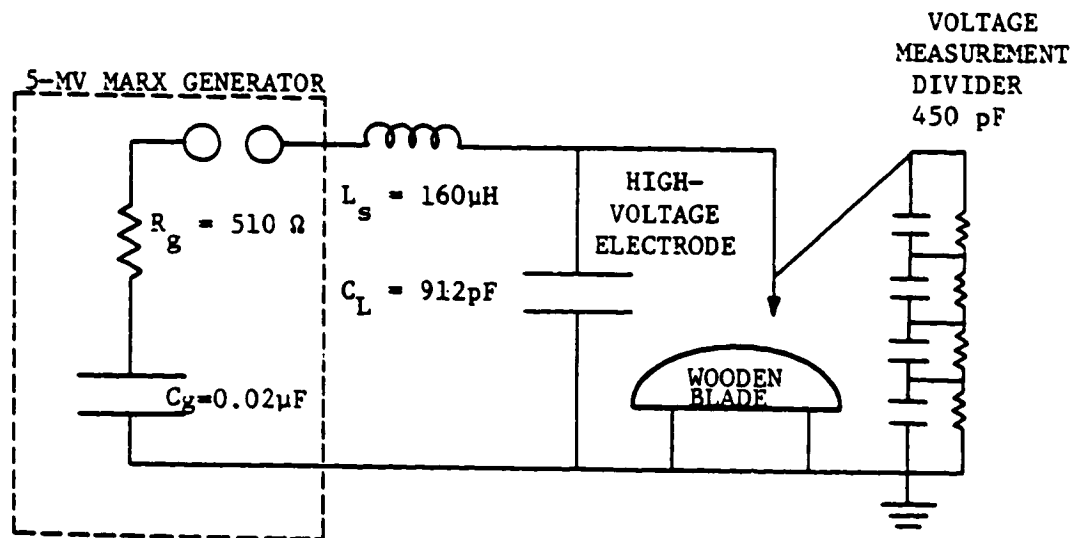


Figure 5.4: Test Circuit for Simulated Strike Attachment Tests.

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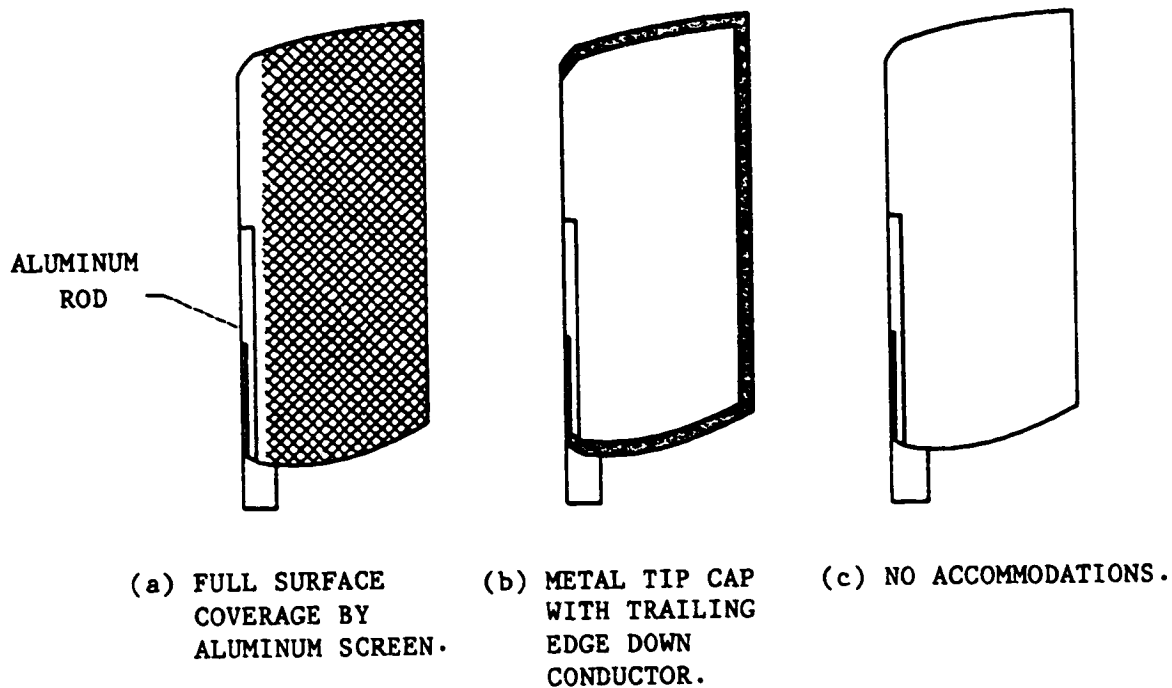


Figure 5.5: Sketch of Wooden Blade Test Specimen.

5.6 CONCLUSIONS AND RECOMMENDATIONS

Blade structures may be damaged by lightning strikes. The damage to metallic blades usually will not interfere with turbine operation, but materials that are nonconductors such as fiberglass and wood need to have some type of lightning accommodation system. The conclusion given by Bankaitis [3] after a series of blade tests [5] is recorded below. Observation of test data on two types of blades and protection systems form the basis for these conclusions.

1. Composite-structural-material rotor blades require a lightning accommodation system whether or not the blades contain internal wiring or metallic components.
2. The basic lightning accommodation concepts examined in these series of tests do effectively contain the charge on the surface of the rotor blade and prevent internal streamer. An aluminium screen covering effectively prevents internal streamer even with a metal conductor component inside the specimen.

3. Adhesive-backed aluminum tape (153 mm by 0.20 mm) properly accommodates currents in excess of 200 kA without structural damage to the composite-material rotor blade, and with only very local damage to the tape itself. The local damage at the point of attachment would be easily repairable at very low cost.
4. Keeping discharge currents on the rotor blade surface, specifically by using conductive paths, prevents structure penetration.
5. A conductive tip cap electrically bonded to the current path down conductor is mandatory to prevent lightning entry into the spar and afterbody from the blade tip.
6. Abrupt direction changes of the current paths must be avoided.
7. Although quantitative data were not obtained, it is known that moisture content in the structure enhances structure penetration by lightning currents.
8. The need to shield internal steel adapters from causing internal streamering between themselves and the tip cap over the length of the internal cavity of the rotor blade has not been clearly substantiated.
9. Induced voltage effects or any secondary effects on instrumentation, structures, or components cannot be assessed.
10. Compliance of the potential lightning accommodation systems with non-interference with television reception has not been defined.

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